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

2011 Microwave Power Transfer Symposium

Thursday, 15 December 2011, 3-6pm, MiRC 102 Georgia Tech Campus

"Shooting for the Stars"

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

2011 Microwave Power Transfer Symposium

Thursday, 15 December 2011, 3-6pm, MiRC 102 Georgia Tech Campus

"Shooting for the Stars"

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

3:00 – 3:15	Introductory Remarks: Prof. Gregory D. Durgin, Room 102A.
3:15 – 4:00	Keynote Talk, Room 102A: "Opportunities and Challenges in Wireless Power Transmission" by Frank Little, Associate Director of the Center for Space Power, Texas A&M.
4:00 – 4:15	Rectenna Device Presentation, Room102A
4:15 – 6:00	Poster Session: Microwave Power Transfer Projects
	Track A, Room 102B: *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. http://www.propagation.gatech.edu/ECE6390/project/Fall2011/Project11.htm
	Track B, MiRC Hallway: *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. http://www.propagation.gatech.edu/ECE4370/projects/projects.html
4:15 – 4:45	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.
4:15 – 6:00	Pizza Party, Room 102A: Pizza and light refreshments served.

General Chair	**Executive Chair**	**Competition Co-chairs**
Darel Preble	Greg Durgin	Blake Marshall, Marcin Morys

Confirmed SSP Judges: Frank Little, Darel Preble, Greg Durgin

Event Patrons: Space Solar Power Institute — The Propagation Group — Georgia Institute of Technology

Posters for ECE 6390 Project Teams

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

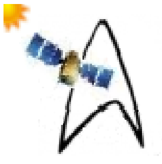
Fall 2011 Space Solar Power

Project Statement

Resource Page

HELIOS

Sunwire



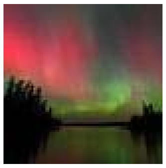
Star Tek Enterprises

Sting-Ray Solar

IRIS

L.E.E.Co.

Death Raytheorp



The Van Allen Co.

HELIOS: Space Solar Power

Christopher Barisich, Fan Cai, Dale Canterbury, Stephen Dumas, Nishad Karandikar
Georgia Institute of Technology

Introduction

The HELIOS project team has proposed the development and implementation of a revolutionary new **S**pace **S**olar **P**ower 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

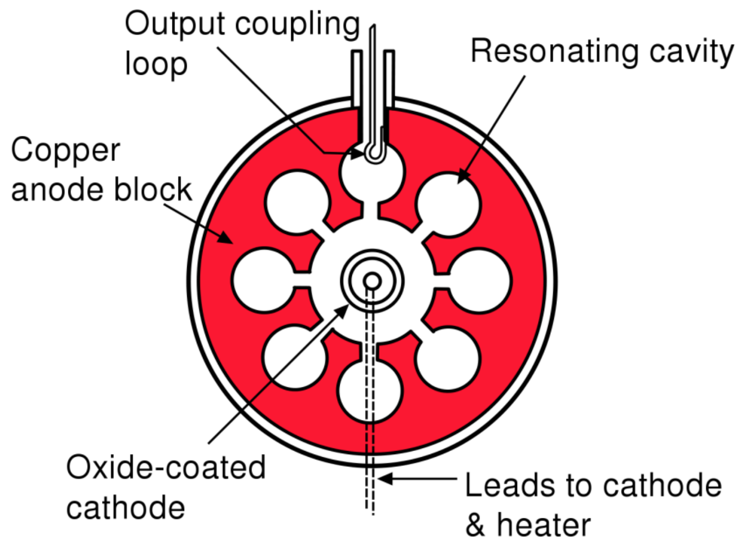
- GEO orbit is used.
- 16 satellites installed by 2028, with a total of 230 satellites by 2050.
- G1, then G2, then G3 rockets will be used sequentially as costs come down to launch equipment for SSP satellites
- Slingshot and conventional launches used to achieve 1500+ launches per year.
- ISS and planned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

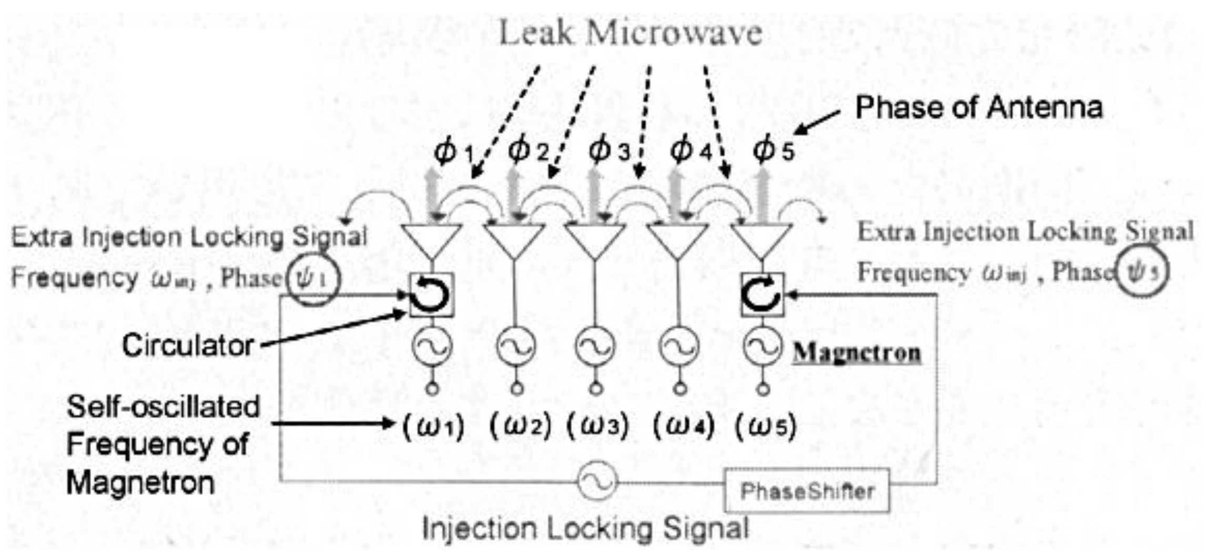
Timeline

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)
2017 to 2021	1. Use G2 rockets to put first SSP into GEO 2. Build rectena 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

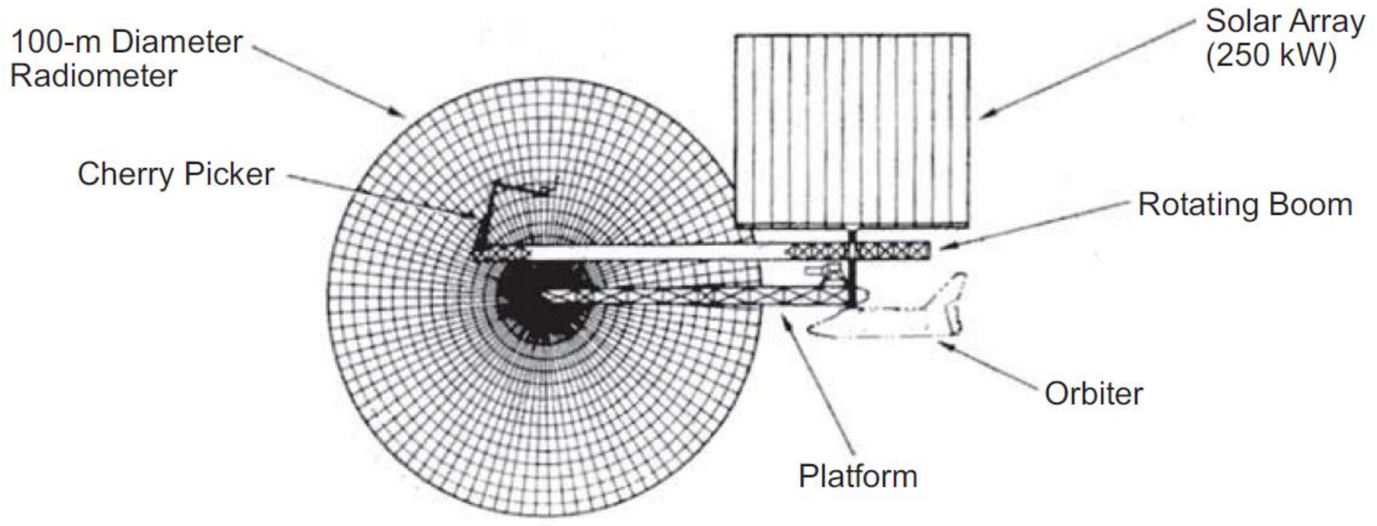
DC to Microwave Conversion

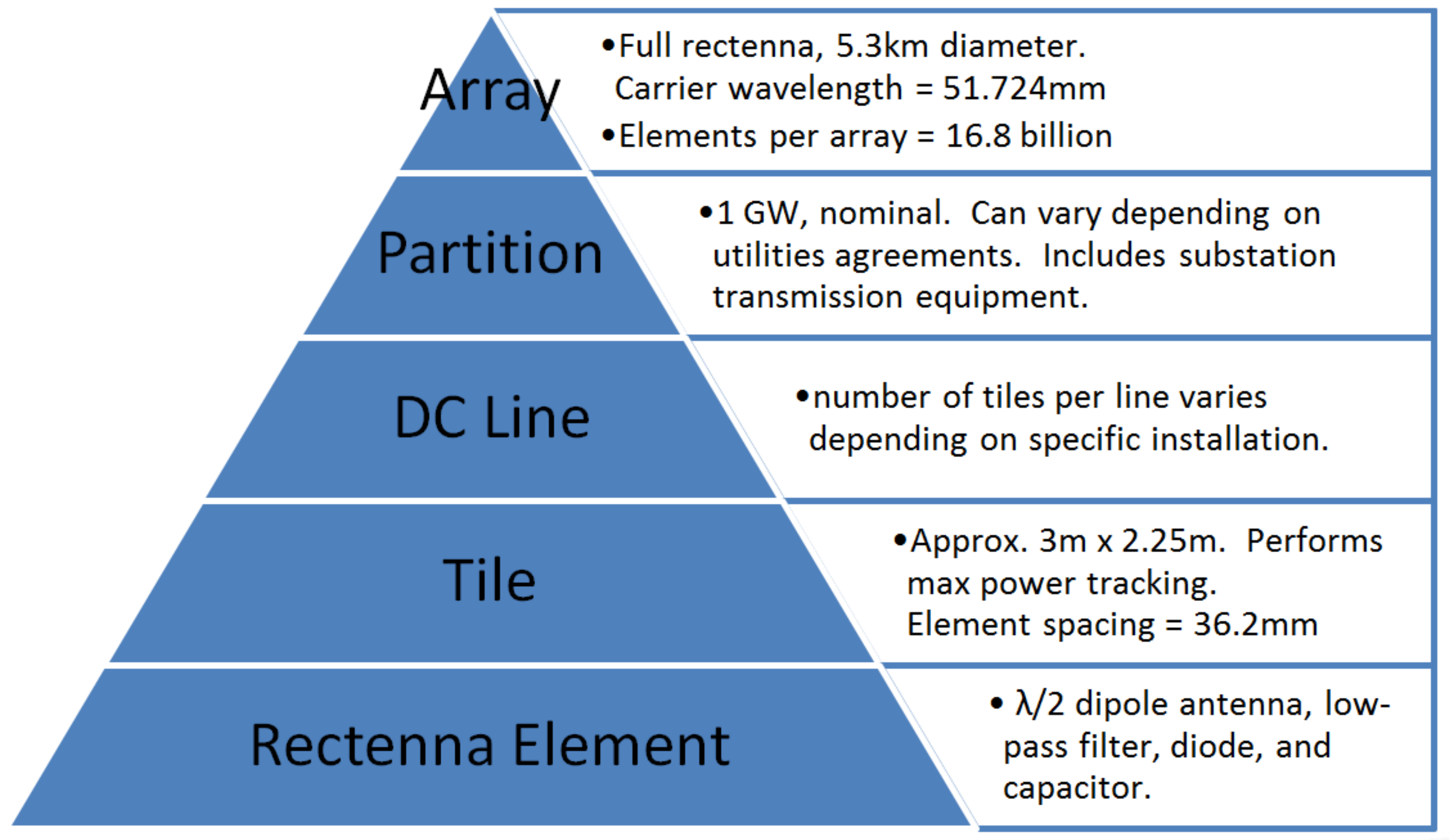
- Output: ~1kW to 10MW
- Frequencies: ~10 MHz to 100 GHz
- Efficiencies: ~70% to 90%
- Poor phase and frequency control
- Costs only ~$13 per kW





TX Antenna and Rectenna





Array
- Full rectenna, 5.3km diameter. Carrier wavelength = 51.724mm
- Elements per array = 16.8 billion

Partition
- 1 GW, nominal. Can vary depending on utilities agreements. Includes substation transmission equipment.

DC Line
- number of tiles per line varies depending on specific installation.

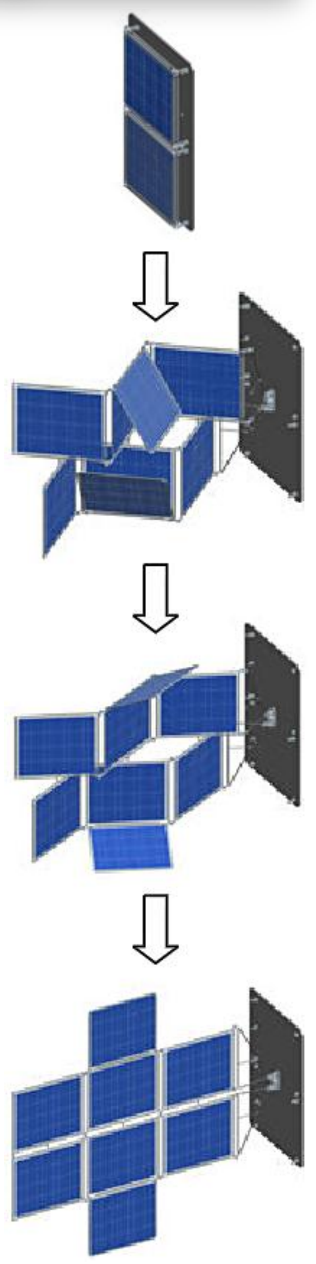
Tile
- Approx. 3m x 2.25m. Performs max power tracking. Element spacing = 36.2mm

Rectenna Element
- λ/2 dipole antenna, low-pass filter, diode, and capacitor.

Space Hardening

- Solar flare particles have energies of 10 MeV to 1GeV, and typical flux densities of ~3×10^{10} p/cm^2
- Galactic cosmic rays typically have energies of about 10 GeV, although some particles can have energies of over 10^{20} eV, and energy density is approximately ~1 eV/cm^3 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.

Photovoltaics Array



Thin-Film Solar Cells

- ~20% cell efficiency
- ~6μm thick, about 100x thinner than crystalline materials
- Made of amorphous-Si or **CuInGaSe$_2$**
- 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 9km^2 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: QPSK
- Coding scheme: CDMA

Earth Station

Parameter	Value
Dish diameter	40m
Gain	45dB
3dB beamwidth	1°
Efficiency	0.8

Satellite

Parameter	Value
Dish diameter	6.8m
Gain	30dB
3dB beamwidth	6°
Efficiency	0.8

Budget

($ in millions)			
Item	Cost Per Item	No. of Items	Total Cost
Launches	$1.5295	632	$966.644
Solar Panels	$450 / 5GW	4	$1,800
Magnetrons	$.0016	2,000	$3.2
Construction	$2,000 / Sat	1	$2,000
SC Cables	$285 / 5GW	4	$1,140
Antenna	$19.238	2	$38.476
Rectenna	$1,500	2	$3,000
Misc. Costs	$1,000	1	$1,000
Total Cost Per Satellite	$9,948	1	$9,948.32
Total Cost For All Satellites	$9,948	230	$2,188,114

Design Summary

Frequency of operation	5.8 GHz
PV generation per Satellite	20 GW (5GW x 4)
Orbit used	GEO (altitude 36000km)
Earth stations per Satellite	2
DC output of Earth station	5 GW
Size of the solar panels	Four 9 km^2 thin film arrays
$/kWh in year 2050	$0.01/kWh
Time duration of project	Phase 1 : 2012 to 2028 Phase 2: 2028 to 2050 Phase 3: 2050 to 2070
No. of satellites launched	Phase 1: 8 satellites (16 downlinks) Phase 2: 222 satellites (444 downlinks) Phase 3: Minimal number of replacement sats
Power conversion	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

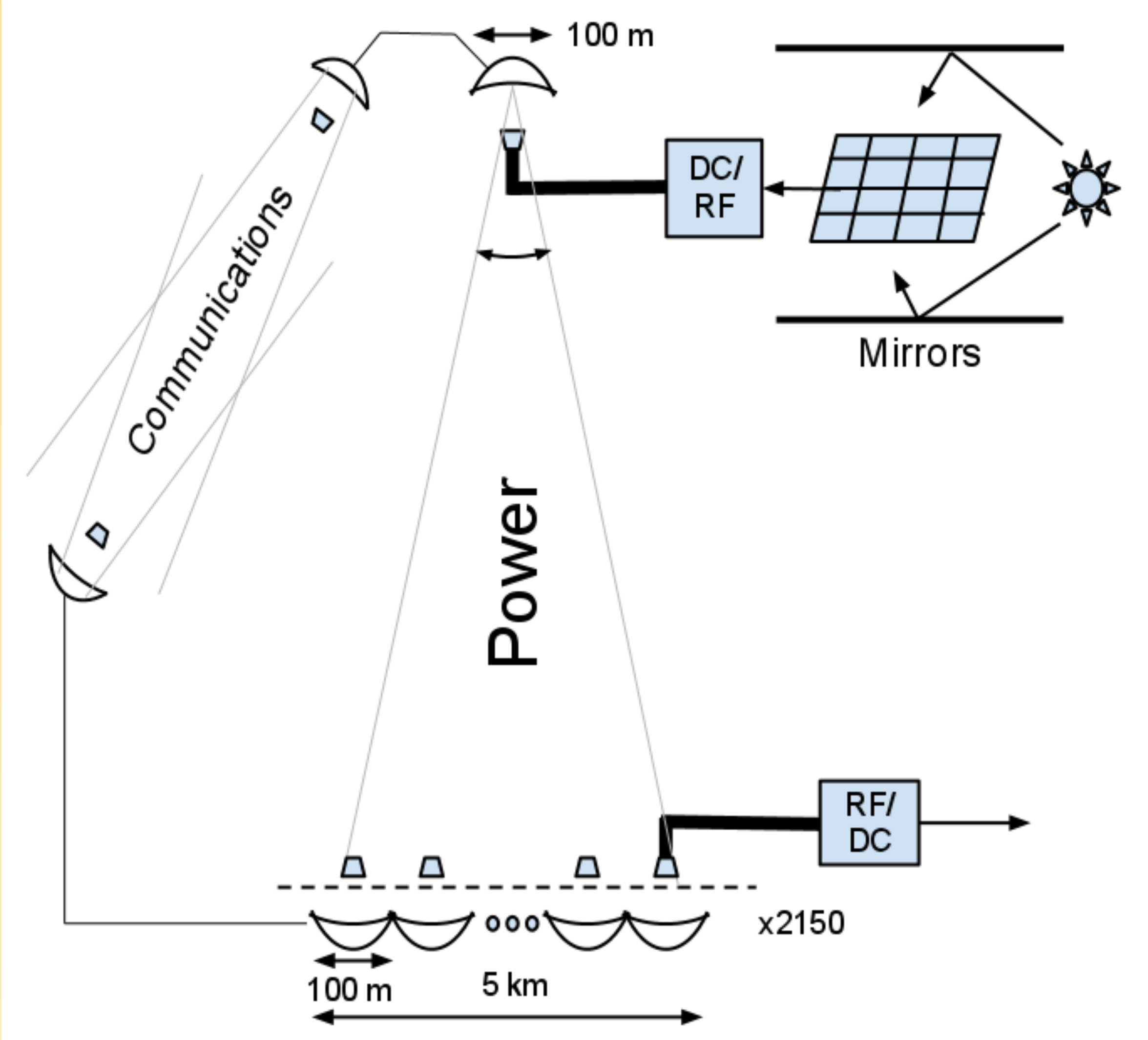
SunWire™

Space-Based Solar Power Solution

Microwave Energy Transfer from GEO

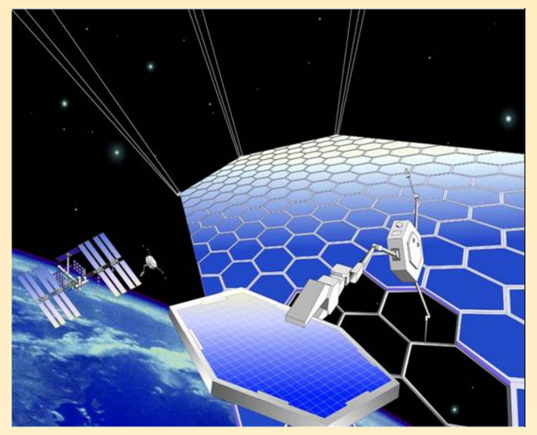
Concept

- 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

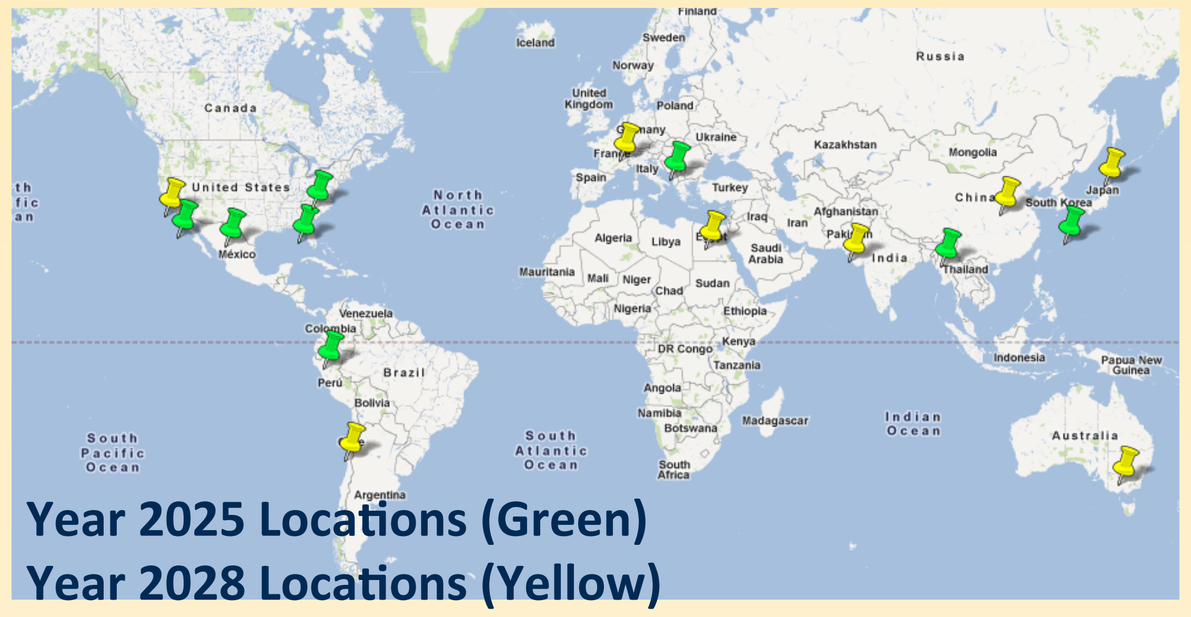


Orbit

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



Earth Stations



Reliability

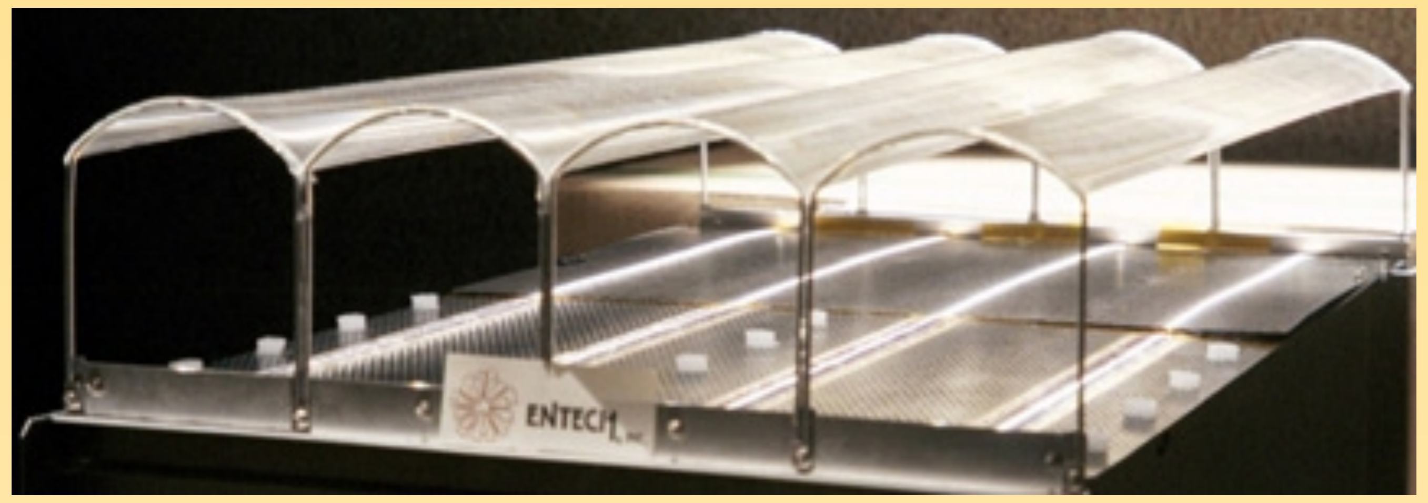
- RADHARD space-certified components
- NASA-certified materials to mitigate outgassing
- Mechanical shielding against space debris and meteorites (< 2mm)
- Use leaded solder to avoid tin whiskers
- Extensive pre-flight/in-orbit testing
- Target lifespan: 50 years

Communication

Satellite-Earth Communications Link Summary	
ES Antenna Diameter	10m
ES Antenna Gain	50 dB
ES Transmit Power (min)	11 dBm
Sat Antenna Diameter	1.0 m
Sat Antenna Gain	30 dB
Sat Transmit Power (min)	7 dBm
Band	5.8 GHz ISM
Bandwidth	150 MHz
DSSS Chip Rate	50 Mchips/s
DSSS Sequence	32 bits
Modulation	QPSK
Uncoded Bit Rate	3.125 Mbps
Coding	Reed-Solomon R=7/8
Available Data Rate	2.73 Mbps

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

Power



Harvest

Mirrors

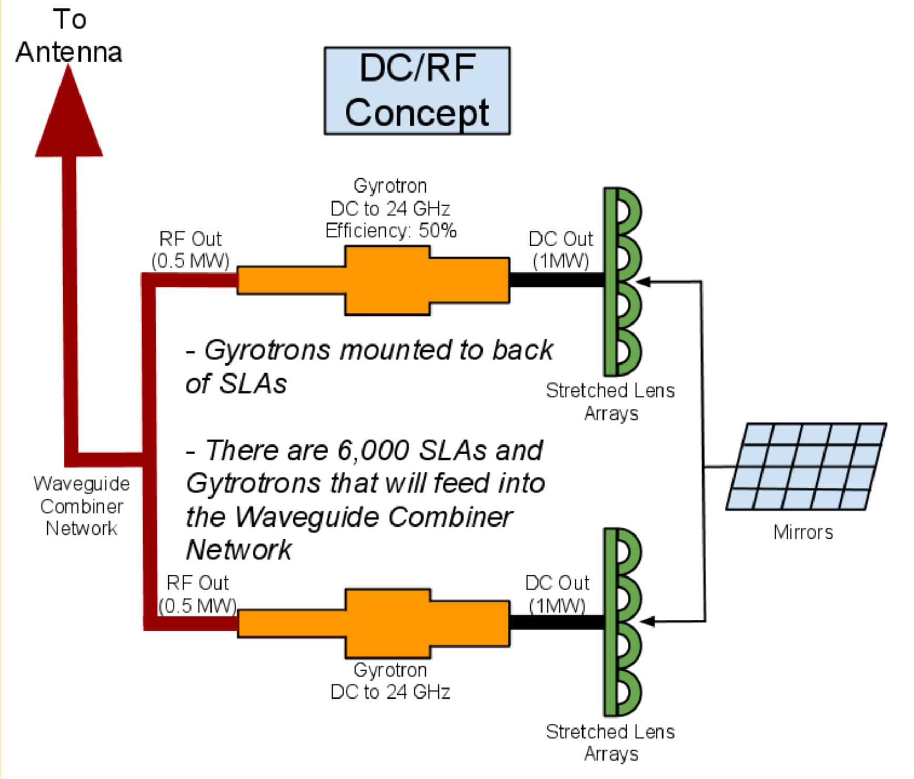
- 5 km x 5 km / 2500 100 m x 100 m
- 94% Reflective
- Polyimide flexible film on metal mesh

PV Array

- 8 Suns concentrations
- 60 % Efficiency in the future
- Capable of 2000 W/kg and 120 kW/m^3
- Size: 1.5 km^2

Conversion (DC->RF)

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



- Gyrotrons mounted to back of SLAs

- There are 6,000 SLAs and Gytrotrons that will feed into the Waveguide Combiner Network

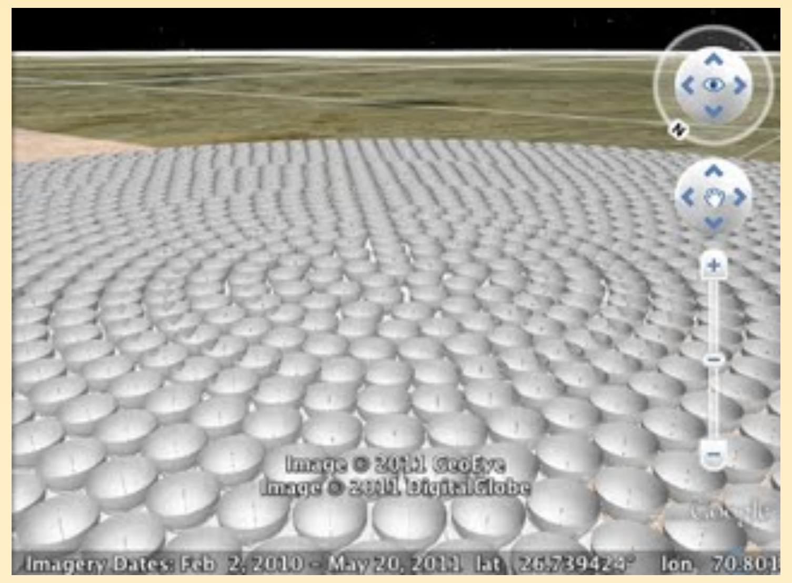
Transfer

Transmitter

- 100 m dish antenna
- 24 GHz
- Surface Roughness: 0.25 mm

Receiver

- 5 km array of 2150 antennas
- 100 m diameter dish
- Surface Roughness: 0.5 mm



Summary

- 1 GW base-load power supply per site
- 8 initial earth sites
- Catalyst for inexpensive transfer into LEO
- 30 years to recuperate cost
- $1.7B yearly income

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

Efficiency Calculation

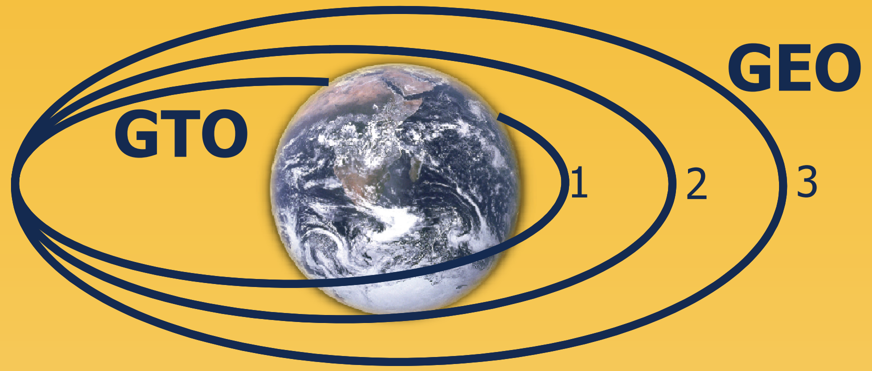
DC-RF	0.5
Free Space / Collection	0.24
Atmospheric Losses	0.89
RF-DC	0.98
Overall Efficiency	**0.103**

ECE6390 · Dr. Gregory Durgin
Hommood Alrowais · Juan Pablo Caram · Matthew Habib · Justin Shapiro · John Watson
Georgia Tech

Star Tek Enterprises:
Space Solar Power Symposium

Georgia Institute of Technology

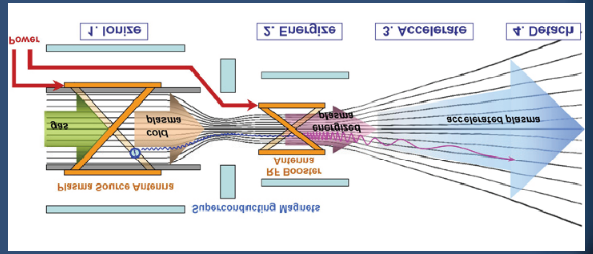
Collaborators: Eleazar Kenyon, Sean Garrison, Cory Ocker, Xiao Yu, John Wilcher



- 2.2 million kg payload (multiple launch)
- Cape Canaveral Launch to GTO (28.5° inclination)
- Low impulse GTO-GEO transfer (Δv = 5.9 km/s)
- Ion engines (F = 210N) -> 2 year transfer

Spacecraft Propulsion

- **VASIMR Ion Engines (42 per sat.)**
    - **I_{SP} = 5000s**
    - **Thrust = 5N**
    - **200kW pwr. consumption**

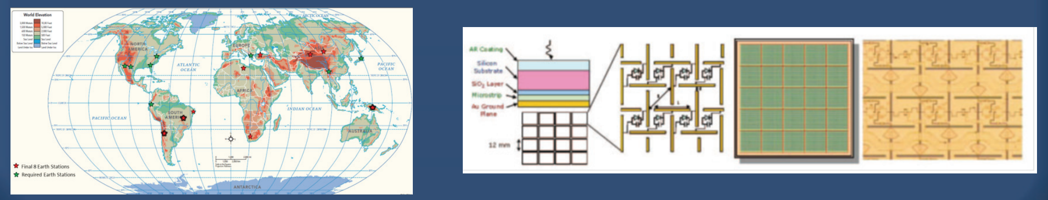


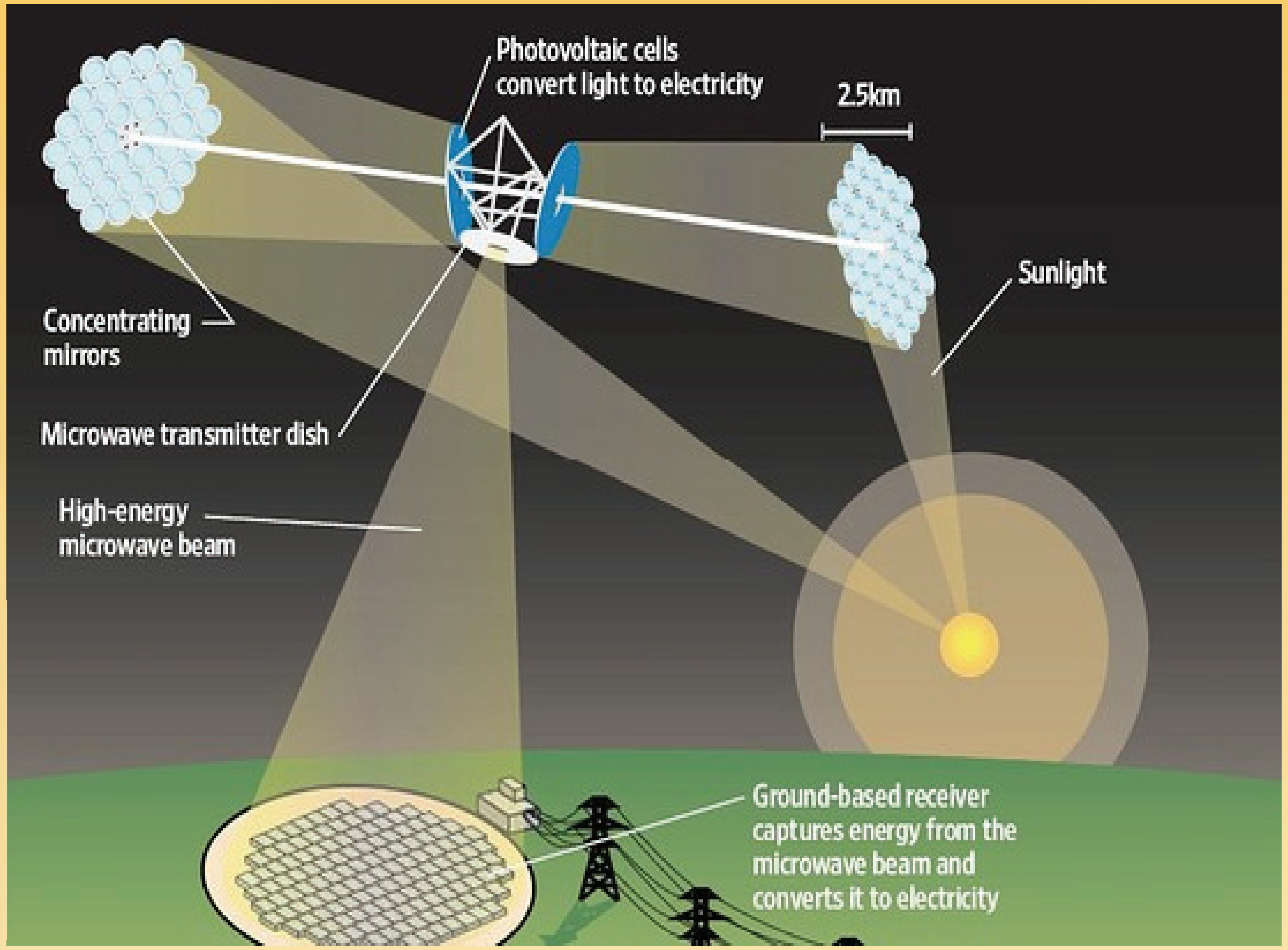
Communication System

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

Ground Stations

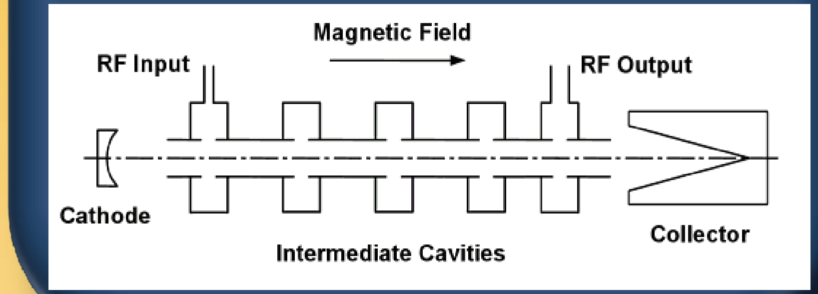
- **Rectenna Array: PCB slot antennas plus diode**





RF Link

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



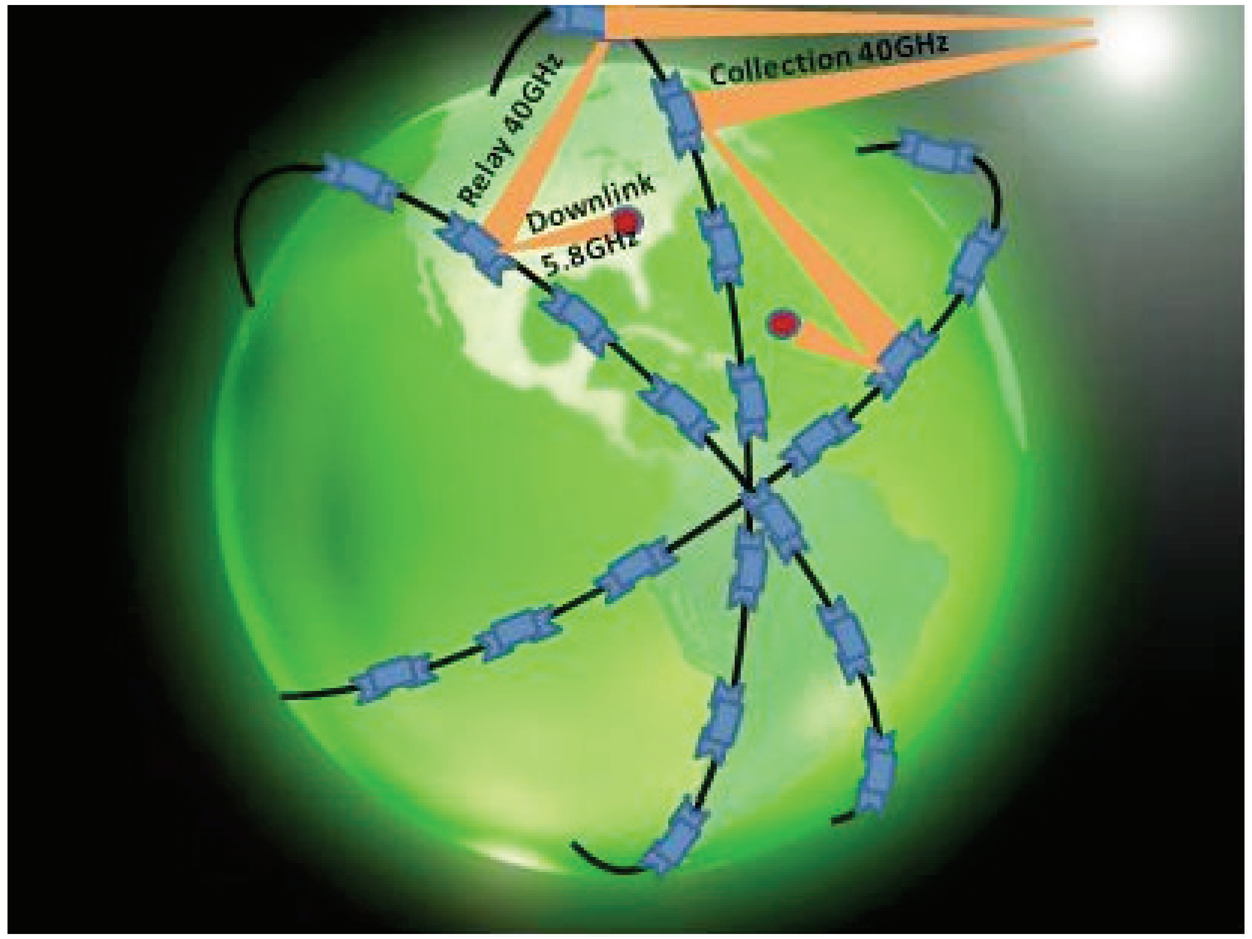
Efficiency	Attenuation Source
99%	Cabling
60%	Waveguide/RF Conversion
90%	Antenna Transmission
58.8%	Atmosphere
80%	Beamwidth
80%	Rectenna

	Total	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30
Revenue ($B)	284.3	15.0	16.0	13.5	13.5	11.0	9.0	9.0	10.0	12.2	11.2	11.2	15.6	18.7	23.4	28.3	32.9	33.9	30.5	30.5
Budget ($B)	267.1	14.4	14.4	14.4	14.4	14.4	17.4	17.4	19.9	14.2	16.6	16.7	17.1	17.8	20.7	19.3	9.0	9.0	9.0	9.0

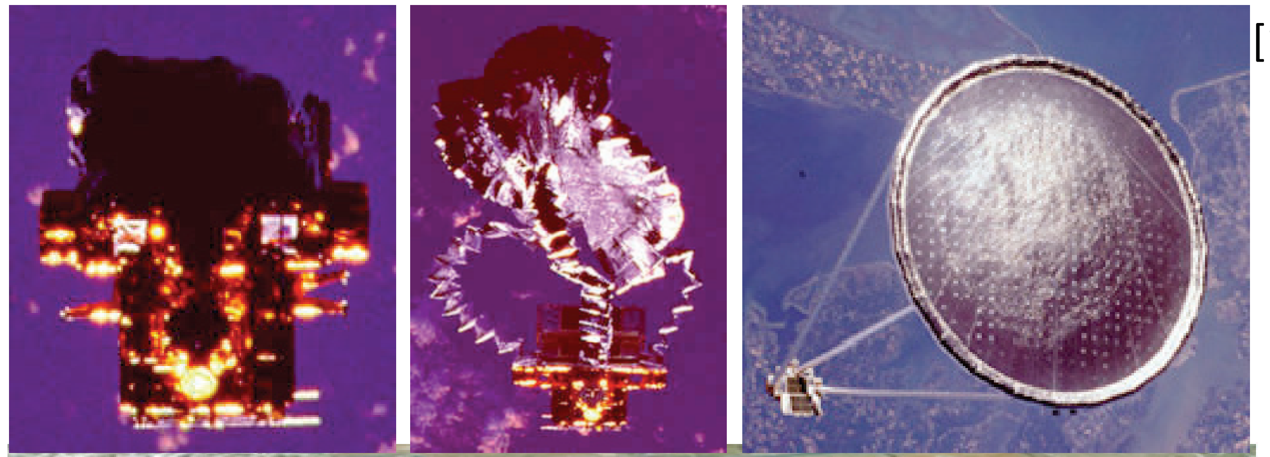
Sting-Ray Solar

Scalable LEO Space Power Grid Concept

ORBITS



ANTENNAS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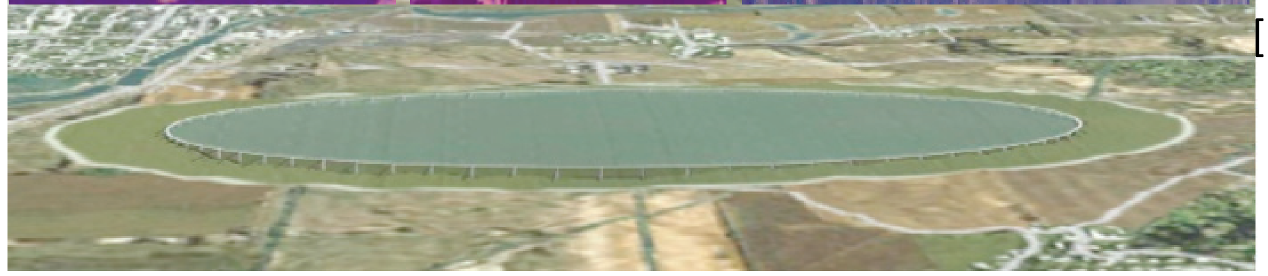
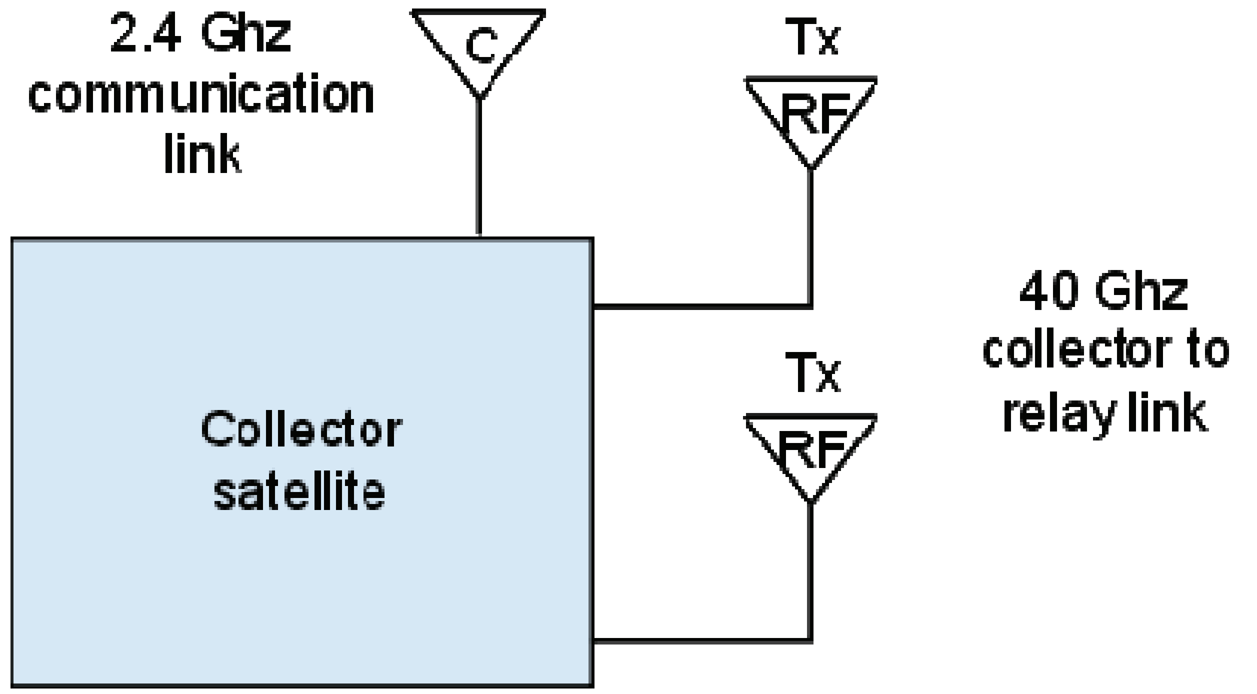

[2]

[1] http://www.lgarde.com/gsfc/spdeploy.htm

[2] Soubel, Andrew K. *Solar Power Satellites and Microwave Power Transmission*

SATELLITE DESIGN


2.4 Ghz communication link

C

Tx

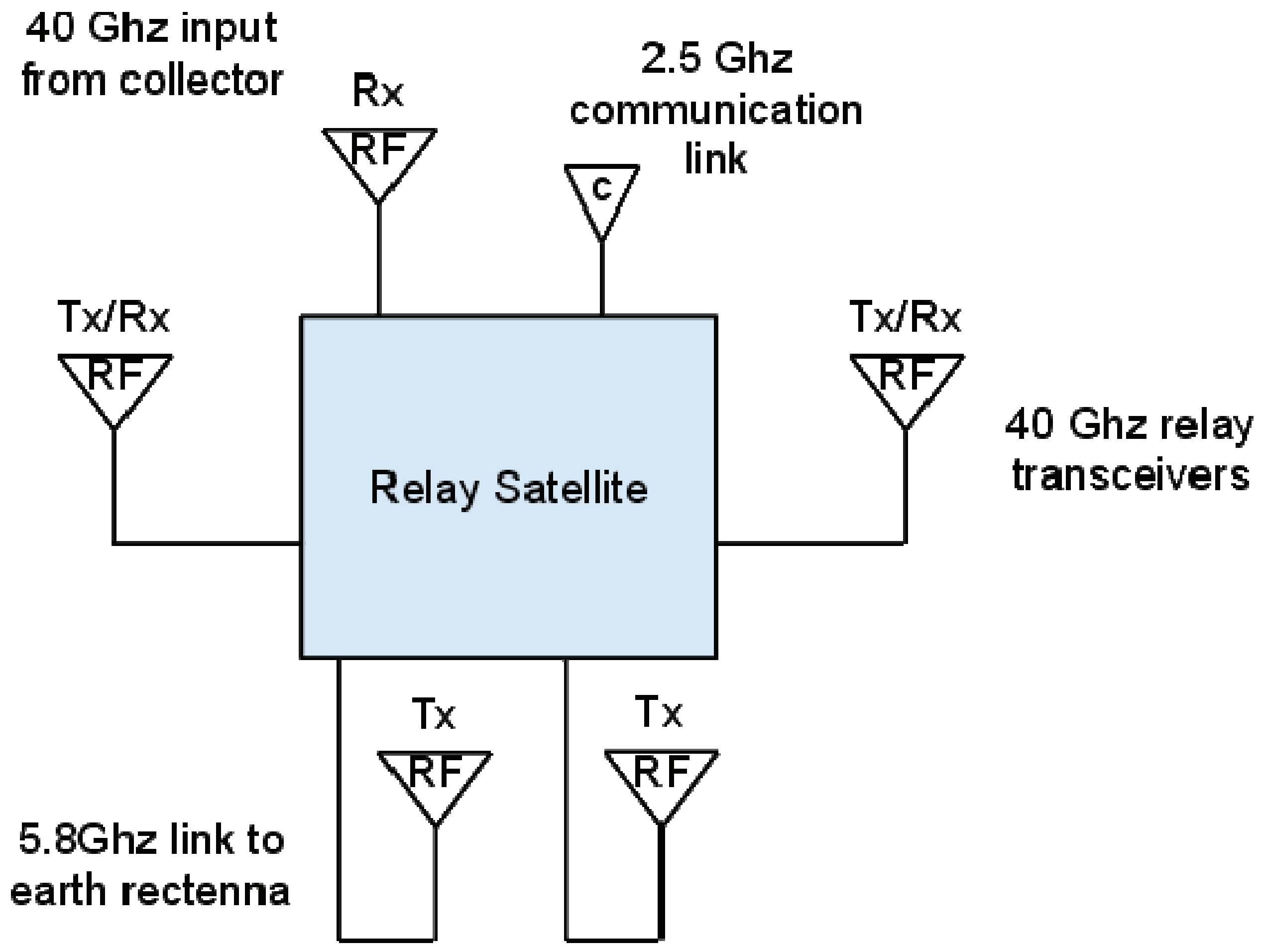
RF

Collector satellite

Tx

RF

40 Ghz collector to relay link


40 Ghz input from collector

Rx

RF

2.5 Ghz communication link

c

Tx/Rx

RF

Relay Satellite

Tx/Rx

RF

40 Ghz relay transceivers

Tx

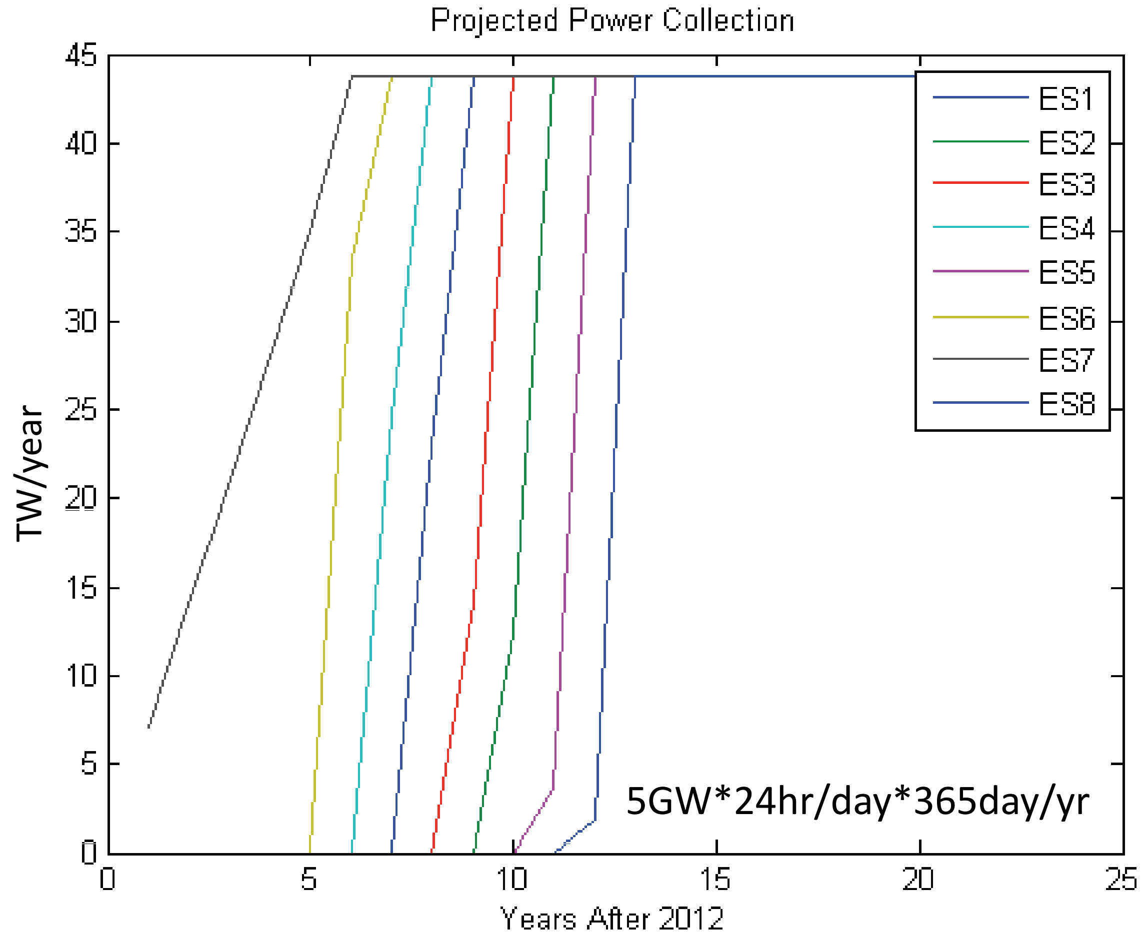
RF

Tx

RF

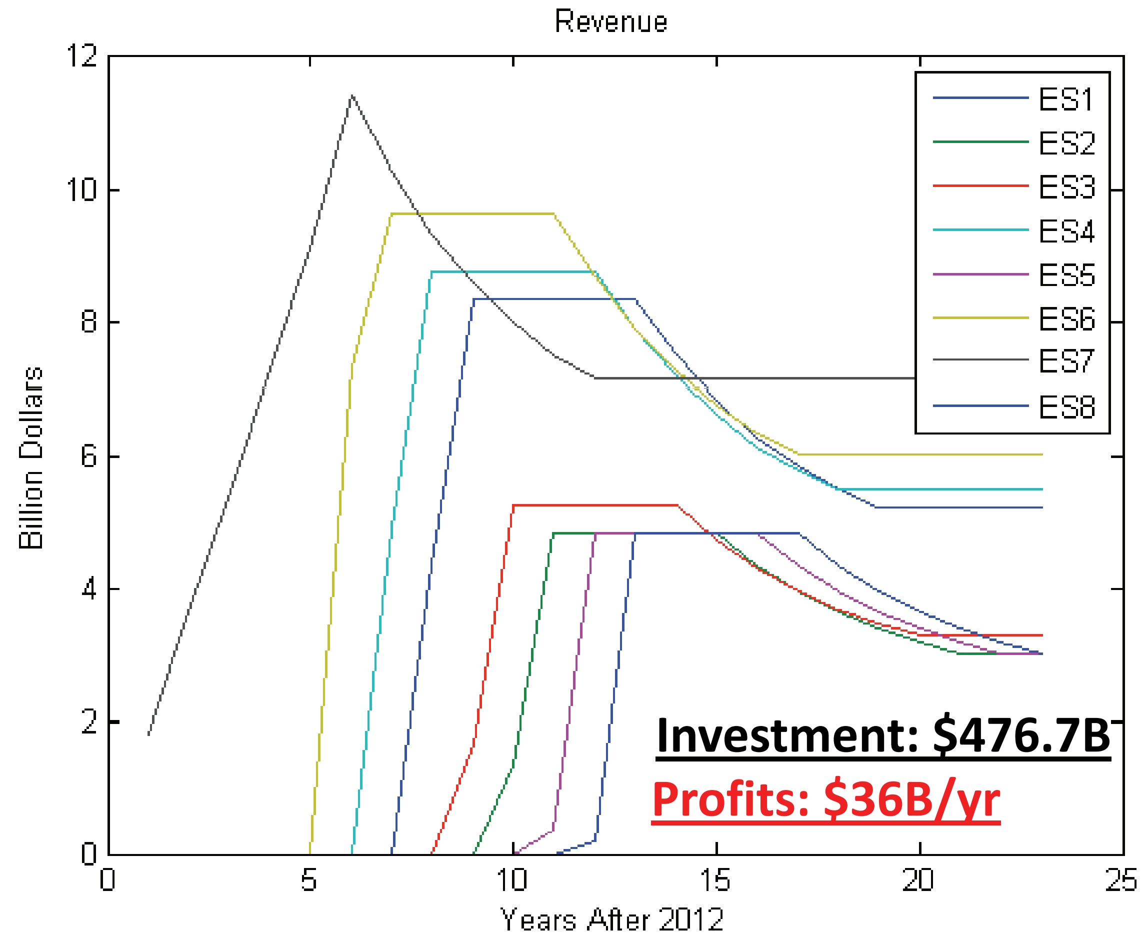
5.8Ghz link to earth rectenna

POWER AND REVENUE



5GW*24hr/day*365day/yr

5GW TO ALL SITES BY 2025



Investment: $476.7B

Profits: $36B/yr

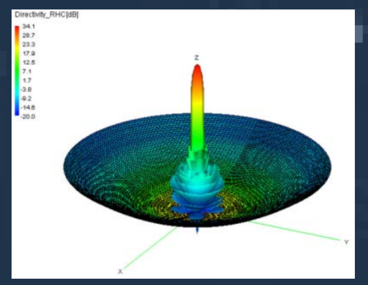
BREAK-EVEN BY 2029

IRIS PROJECT: SPACE SOLAR POWER

Mason Nixon
Austin Scheidemantel
Andrew Punnoose
Diapa Sanogo
Tri Pho

Earth Station Collector and Rectenna

Antenna Design



Primary Considerations

1. Gain Pattern
2. Center frequency (24.125GHz)
3. Bandwidth
4. Polarization – Circular
5. Beam taper
6. Sidelobe restriction

(Must also describe Beamwidth (HPBW), Sidelobe level/Front-to-Back Ratio, Radiation Resistance, Max Rated Power, VSWR)

Antenna Features

Cassegrain-fed Architecture
Min. Subreflector Diameter = 0.249m (20λ)
Circularly Polarized

Dish Antenna Trade-off

$D_1D_2=\lambda r$
Assuming D_2 (in the sky) = 100m,
D_1 = ((3e8/24.125e9)*20.2e6)/100 = 2.512e3m
r= 20.2e6m (worst case for MEO)

Array of Antenna Circuits

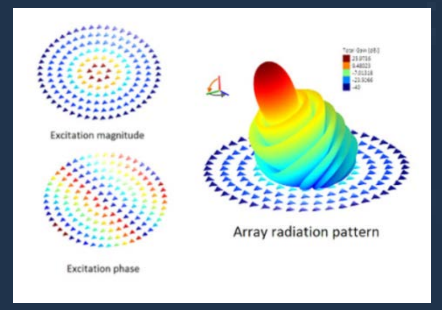
- Each Rectenna circuit can produce an output between 3 and 10Kw per square meter DC power using monolithic rectennas as our approach in rectifying the received microwave power. This is not enough for our overall generation of DC power for the earth power grid.
- We need to put multiple rectenna circuits together to create an array of rectenna circuits.
- 100000 to 333333.33 square meter rectenna array would be enough to produce at least 1GW of electric power and deliver it to the Earth power grid.

$$\text{Microwave Power Reveiced by Each Rectenna} = \frac{\text{Total Intercepted Microwave Power by Dish Antenna}}{N}$$

- The DC to DC power conversion can achieved with a total possible efficiency of 76%. This can efficiency result can be expected if a good matching of components can be realized

Array shape: Circular

Element spacing, d = (1900/2π)*λ = 3.75m
Element excitation amplitude – fixed amplitude for steering
Element excitation phase – varies on desired direction
Array element pattern



Array Elements

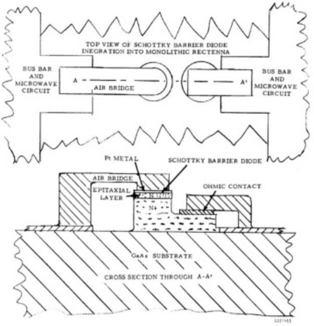
element diameter, D = 300m
dish depth, d = 25m
f (focal length) = (D^2/16d) = 225m,
f/D = 0.75,
\# elements in array = 10

Other Parameters

By the pattern multiplication theorem:
Array pattern = Array element pattern x Array factor(AF)
Array diameter = 2,512 km
Beamforming: MMSE (Minimum Mean Square Error)
Total Losses
Friis Transmission:
$P_r = P_t + G_t + G_r + 20 \log (\lambda / 4 \pi) - 20 \log (r)$ - Other Losses
Other losses = 9.6dB
P_r = 6.251 GW
Electrical Efficiency: 76%
Delivered Baseload Power: 4.75 GW

Approach in Rectenna Circuit Design

- The Collector dish on Earth will need a front-end circuit which will be able to convert microwave power to DC power. This is the purpose of the rectenna circuit which will receive the microwave power through the collector dish. The overall system is composed of the collector dish and the rectenna circuit is called the rectenna
- At 24.125GHz, we will use a monolithic approach in which the diodes and all the circuitry are built on a Gallium Arsenide (GaAs) substrate which we know can function at frequencies above 250GHz.



Communications

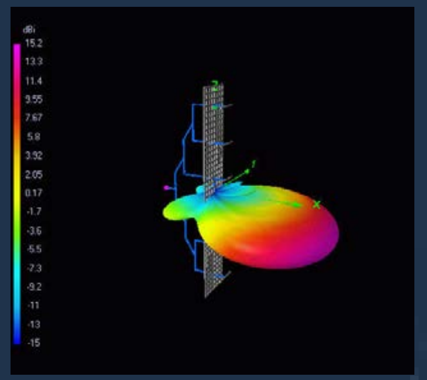
Designed with security in mind – protection from interception, jamming, spoofing

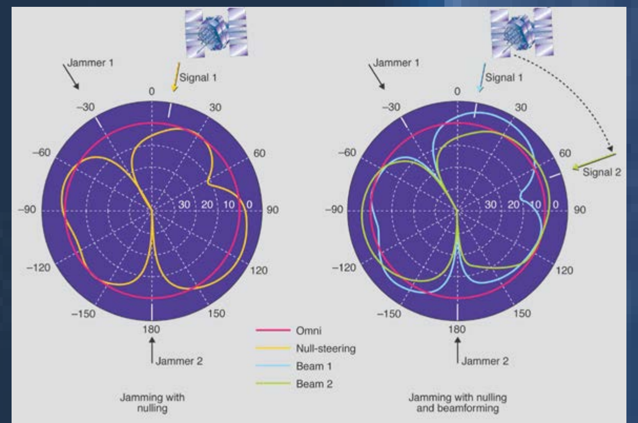
Table C1. Communications Sub-System Overview
Modulation Scheme
0.125 GMSK-FH
Carrier Frequency
Uplink 44 Ghz Downlink 20 Ghz
Occupied Bandwidth
Uplink 500 Mhz Downlink 500 Mhz
Uncoded Data Rate
2.0 Mbps
Coding
Rate 1/2 Turbo Coded
Data Security
ECDSA-384

Satellite-side Physical Hardware

Phased-element Array Antennas

- Fast pointing due to electronic steering
- Capable of shaping the antenna gain pattern dynamically. (Shown below on the left)
- Useful for casting a null in the gain pattern where an attempted jamming signal is detected (Shown below on the right)

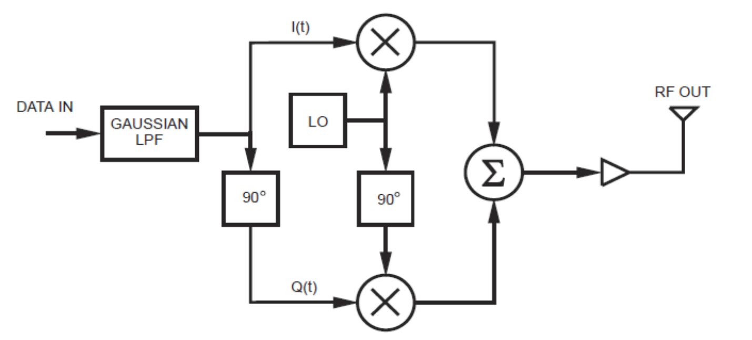




Modulation Specifications

Gaussian Minimum Shift Keying – Frequency Hopped – BT 1/8

- GMSK used for efficient spectral bandwidth and independence from power amplifier linearity
- Frequency hopping used for interception obfuscation
- A coherent GMSK modulator is shown to the right



Transport Layer Encryption

384-bit Elliptic Curve Digital Signature Algorithm

- A step up from the currently recommended 256-bit ECSDA encryption for level SECRET information

Satellites

Orbit Design

The orbits chosen for this mission are two Borealis orbits and a high altitude circular orbit. The inclination and angle of these three orbits were tuned such that the orbits are sun synchronous. A sun synchronous orbit maintains its angle with respect to the Sun, meaning that the solar panels will always point towards the Sun without a need for active control (disregarding perturbations). The Borealis orbit was chosen for its high ellipticity that allows for long periods of coverage of the Northern hemisphere. The circular orbit was chosen to cover the ground stations located in the Southern Hemisphere. Each orbit contains four satellites, for a total of twelve satellites. Shown below is a table of the orbit parameters.

Orbit	Long. of Asc. Node (deg)	Perigee Altitude (km)	Apogee Altitude (km)	Inclination (deg)	Arg. of Perigee (deg)
Borealis 1	0	633	7605	116.6	270
Borealis 2	180	633	7605	116.6	270
Circular	131	5486	5486	150	0

Subsystems

Power

The power transmitted to ground stations is gathered using thin film solar panels with an efficiency of at least 16.8 kW/kg. At this efficiency, 595,000 kg of solar panels must be used to generate the desired 10 GW. Accounting for a 15% degradation in efficiency every 5 years, a total of 700,000 kg of solar panels must be launched initially, and approximately 105,000 kg of solar panels must be replaced every 5 years.

Stationkeeping

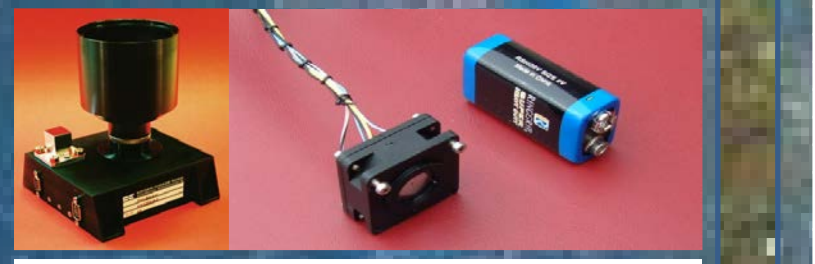
In order to maintain desired orbits, stationkeeping maneuvers must be performed. These maneuvers will be performed using a chemical thruster, requiring approximately 10,200 kg of fuel annually. This fuel will be provided through periodic fuel resupply missions.

Thermal

The thermal conditioning system will consist of passive coatings placed on the rear of the solar panels, allowing the solar panels to radiate excess heat to maintain operating temperatures. The main body of the satellite will perform thermal conditioning through the use of active heat piping.

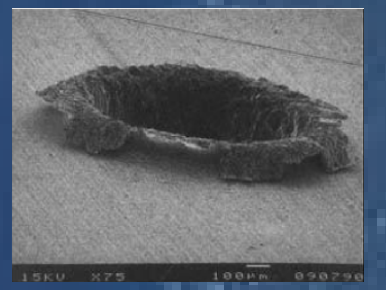
ADACs

Magnetoplasmadynamic thrusters were chosen to provide attitude control, due to the need to constantly maintain the orientation of the solar panels towards the Sun. These thrusters, while expensive, provide high levels of thrust (relative to other electric thrusters) and are extremely efficient.

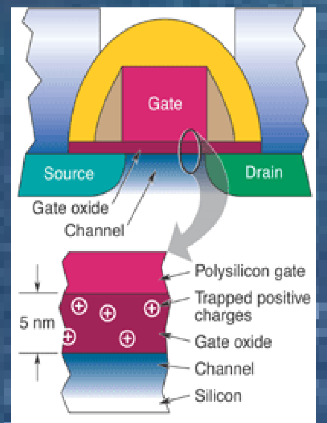

Star tracker (left) and Sun sensor (right) (from www.spaceyuga.com)

The Space Environment

- Micrometeorite Environment
- Rad Environment & Effects On Hardware
- Impact On Mission and Reliability



Impact crater in Aluminum
Source: NASA Reference Publication 1408, "Meteoroids and Orbital Effects On Spacecraft."

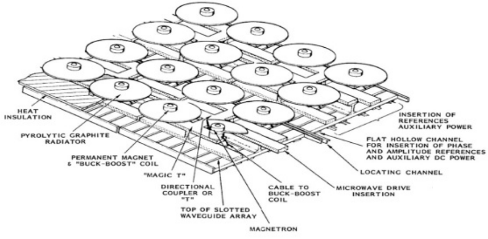


Cross section of an NMOS transistor showing the gate oxide and conducting channel formed between the source and drain. The trapped charges shown in the inset are responsible for failure.

Microwave Power Hardware

Magnetron Directional Amplifier (MDA)

- A microwave device is needed to convert the collected DC power from the photovoltaics cells to RF microwave power. This process is done through a Magnetron Directional Amplifier (MDA).
- The MDA is composed of a conventional magnetron (similar to what is used in microwave ovens) with the addition of a passive directional device (a ferrite circulator or a "magic –T"), the output sensors and compensators for both amplitude and phase tracking, and the feedback control circuits.
- As each MDA has a limit in how much DC power it can intake, multiple MDAs can be put together to form an array of MDAs. This is called a power module.
- The power module is composed of four radiating units. In turn, each radiating unit is composed of two MDAs.
- The power module can generate great microwave power outputs; in the order of GW of power.



Benefits of MDA

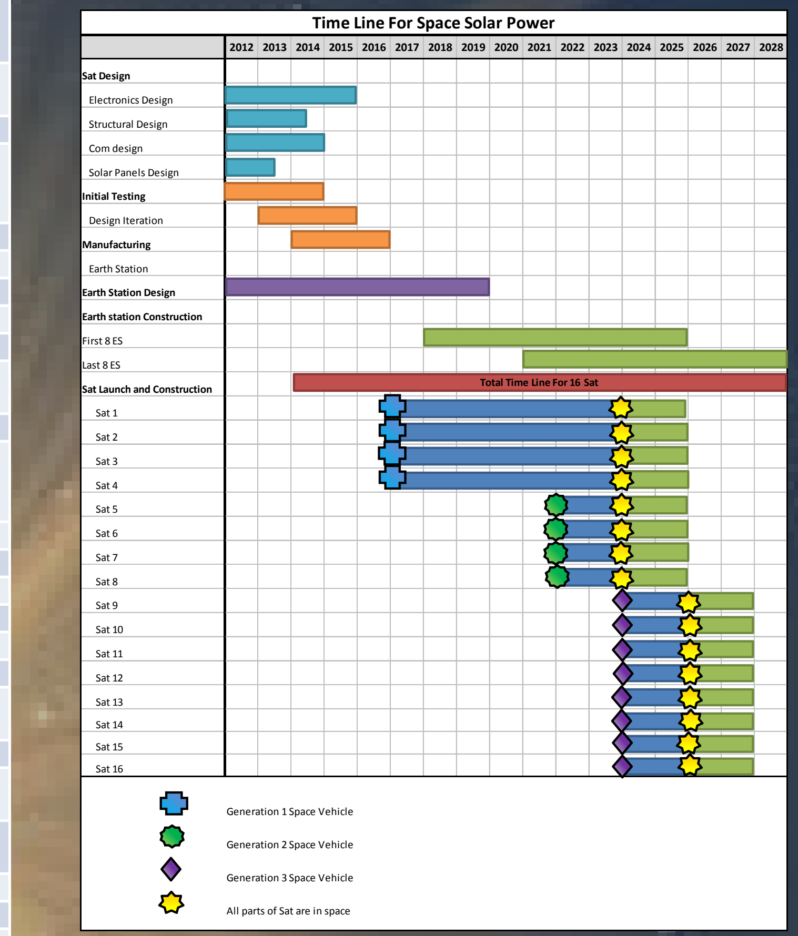
- Phase and amplitude tracking capability of magnetron directional amplifier.
- Exceptionally high signal to noise ratio
- Long life based because of low operating temperature of the carburized thoriated tungsten cathode.

Budget And Logistics

Estimated Budget for 16 SSPS and Earth Stations

	weight in (Kg)	material cost	man hour cost including building	
Main Power transmitting dish	186,000	$10,000,000	$35,000,000	
Electronics				
Electronics for satellite systems other then com and power tx	30	$2,500,000	$15,000,000	
Communications dishes				
RX Dish and Components	50	$350,000	$1,250,000	
TX dish components	50	$450,000	$1,750,000	
Structural				
Support Structure	125	$550,000	$1,200,000	
Extra Structural Protection form Micro meteorites	25	$50,000	$350,000	
Power Generation				
Solar Panels	6,000,000	$1,829,473,810	$2,500,000	
Added solar panels to account for deterioration	105,000			
Power Cabling	100	$3,500,000	$1,500,000	
Antenna Probe	11	$1,200,000	$480,000	
Copper Vanes	44	$750,000	$300,000	
Copper Shell	45	$890,000	$356,000	
Ceramics	30	$400,000	$160,000	
Filament	8	$340,000	$136,000	
Magnetic Circuit Including SM Co Magnets	266	$3,500,000	$1,400,000	
Phase Control				
Voice Coil and Inductive Tuner	64	$650,000	$260,000	
Amplitude Control Power Conditioning				
Buck-Boost Coil	200	$1,300,000	$520,000	
Cooling				
Pyrographite Radiator	350	$4,500,000	$1,800,000	
Thermal	446	$350,000	$1,000,000	
Stationkeeping	10,213	$350,000	$1,000,000	
Attitude Control	55,125	$1,500,000	$50,160,561	
Transverse fuel	4,900	$350,000	$550,000	
2 Robot builder Arm	100	$425,000	$1,200,000	
Total Mass (Kg)	6,363,080.94	→Convert into Mass in lbs	13,998,778	
Cost to build Without launch Cost	$1,976,251,370			
Average Launch Cost per satellite see attached table requires all 16 satellites to be launched to achieve pricing	$2,550,000,000.00			
Extra Maintenance Cost Per Sat	$12,000,000.00			
Total cost per satellite	$4,538,251,370			
Total cost for 16 satellites	$72,612,021,923			
1 Earth station costs (including all Rx dishes)		$100,000,000	$26,000,000	
Total Earth station costs (including all Rx dishes)		$1,600,000,000.00	$416,000,000.00	
Producing 1 GW per station total return possibility				
16 Satellites	$74,628,021,922.66	$672,555,700,899		
32 Satellites	$40,000,000,000.00	$1,345,111,401,799		
16 Satellites	$74.63	$672.56	In Billions	
32 Satellites	$40.00	$1,345.11	In Billions	
Producing 4.75 GW per station total return possibility				
16 Satellites	$74,628,021,922.66	$3,194,639,562,277		
32 Satellites	$40,000,000,000.00	$6,389,279,124,554		
16 Satellites	$74.63	$3,194.64	In Billions	
32 Satellites	$40.00	$6,389.28	In Billions	
	Only Delivery 1GW	With our Solution and Efficiency Delivering 4.75GW per station		
Rate of Return (ROI) X times investment Original investment	9.0	42.8		
If 16 more sat and earth stations were added	17.6	159.7		
Rate of Return (ROI) in %	901%	4281%		
If 16 more sat and earth stations were added in %	1760%	15973%		

Time Line For Satellite Launch



Launch Costing and Scheduling

Cost Schedule for Space Launches

		Flights per year	Total lbs Launched	lbs left to get to space	Cost
Generation 1 Year 1	1st year	20	400,000.00	111,590,225	1,200,000,000.00
	2nd year	20	400,000.00	111,190,225	1,200,000,000.00
	3rd year	20	400,000.00	110,790,225	1,200,000,000.00
	4th year	20	400,000.00	110,390,225	1,200,000,000.00
	5th year	20	400,000.00	109,990,225	1,200,000,000.00
Generation 2 year 1	6th year	100	2,000,000.00	107,990,225	2,000,000,000.00
	7th year	200	4,000,000.00	103,990,225	4,000,000,000.00
	8th year	400	8,000,000.00	95,990,225	8,000,000,000.00
	9th year	800	16,000,000.00	79,990,225	4,800,000,000.00
Generation 3 year 1	10th year	3200	64,000,000.00	15,990,225	6,400,000,000.00
	11th year	3200	64,000,000.00	63,980,449	3,200,000,000.00
	12th year	3200	64,000,000.00	-19,551	6,400,000,000.00

Solar Panel Cost

Cost for Solar Panels	
Power per	16.8 KW/Kg
Total Power (MW)	160,000 MW
Cost per Watt from Ken Zweibel, NREL	$0.19
Total Cost Per Sat	$1,829,473,809.52

Added Cost and Weight From Space Hardening

Estimated added weight, Time, and Manufacturing Cost For long Term Space Solar Power Reliability

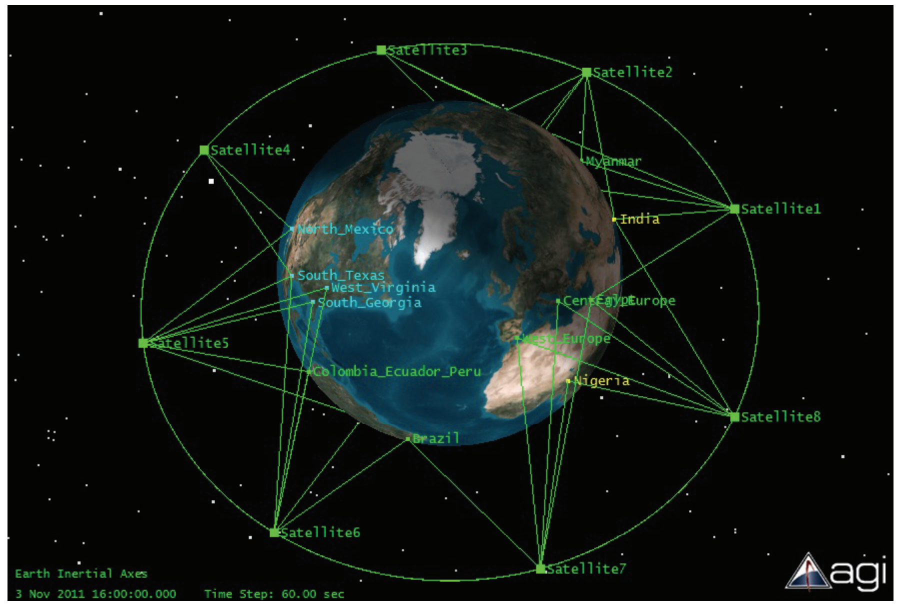
Percent weight Increase By Considering

	Rad		Micro Meteorites	
	Weight Increase	Devolvement Cost Increase	Weight Increase	Devolvement Cost Increase
Electronics	7-23%	60-120%	0-3%	3-7%
Solar Cells	1-3%	3-7%	4-7%	3-6%
Satellite Structure	0-2%	13%	17%	23%

Low Earth Electric Co.

Brendan Dessanti, Mitchell Powner, Ryan Redmond, Christian Vorndran

Orbital Parameters



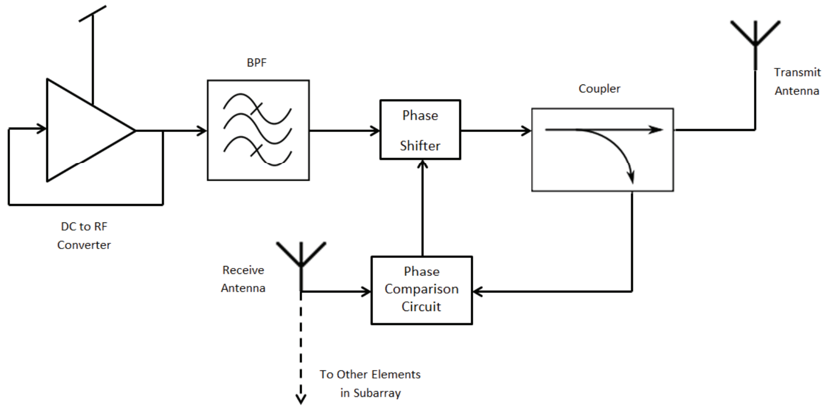
STK Simulation Of MEO Constellation

Parameter	Value
Orbit Altitude	5000km
# of Satellites	8
Orbit Type	Equatorial
Antenna Area	2.81e5 m^2
Antenna Specific Mass	33.9 kg/m^2
Antenna Mass	9.53e6 kg
Additional Antenna Mass (2028)	9.53e6 kg
Total Spacecraft Antenna Mass	1.91e7 kg

Summary Of Orbital Parameters

Uplink	Downlink
Firmware / Software Updates for Sub-systems	Telemetry Data
Reconfiguration Commands	Sub-system Status Alarms and Diagnostics
Handshakes (encryption, coding, etc.)	Power Generation and Transmission Statistics
	Keep alives

Sample of Necessary Data Transmissions



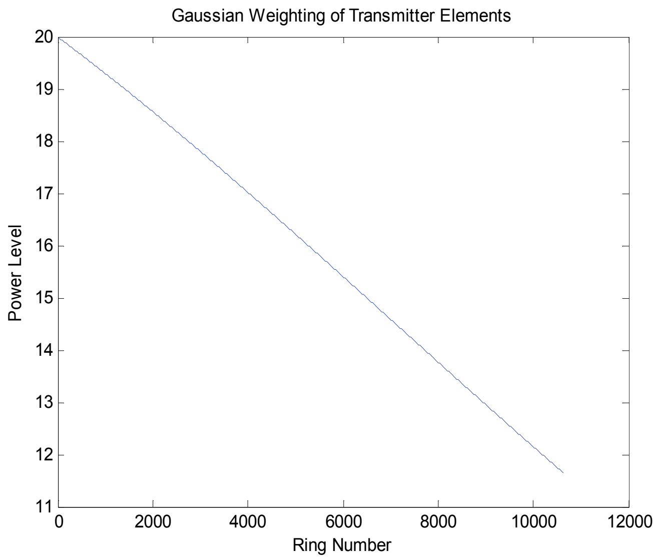
Power Transmitter

DC – RF Conversion

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

Power Beam

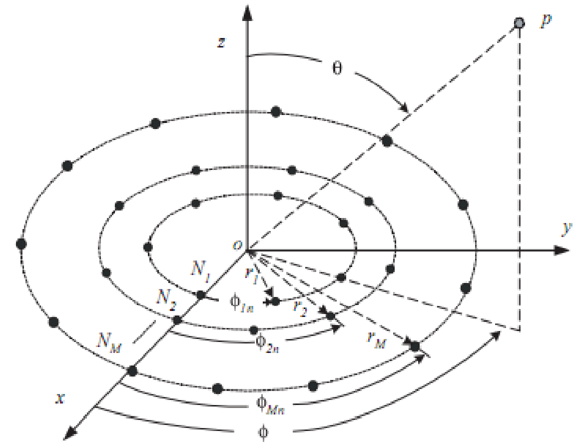
- 600 m diameter phased array
- $\lambda/_2$ element spacing
- Gaussian power tapering:



- Retrodirective pointing (left)

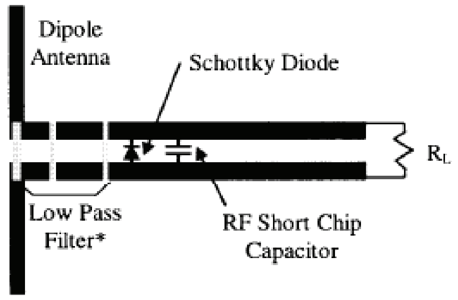
Rectenna

Array



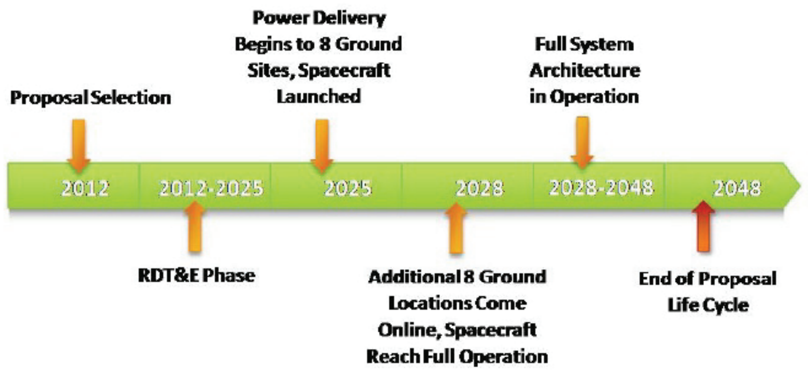
- 1.982 km diameter circularly concentric array
  - λ/2 element and ring spacing
  - 38,318 concentric circles

Elements

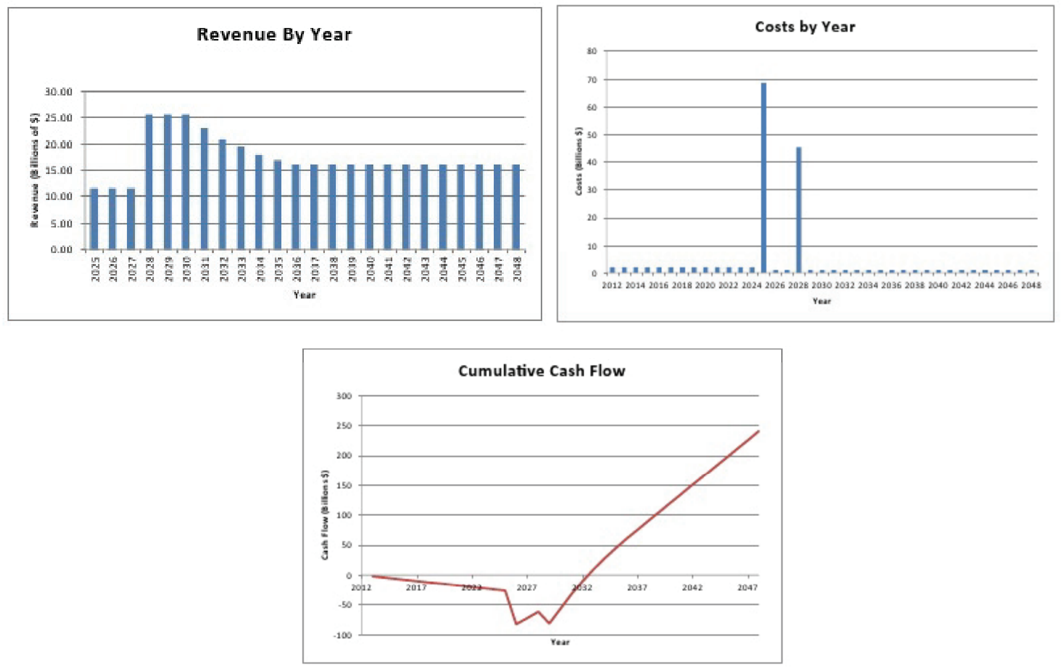


- Printed dipole, CPS line
- Si Schottky diode rectification
- 82.7% overall efficiency

Budget and Timeline



Proposal Timeline



Revenue, Costs, and Cash Flow Analysis

Parameter	Value
Spacecraft Lifetime (years)	23
End-to-End Efficiency	0.4
Total System Cost	$162 billion
Total Power Output	3.15E+12 kWh
$/kWh	**0.051**

Economic Summary

ECE 6390

Death Raytheon

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

Malka Kadish,[1] Thomas Pappas,[2] Gregory Watkins,[1] Breneman Whitfield[1]

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.

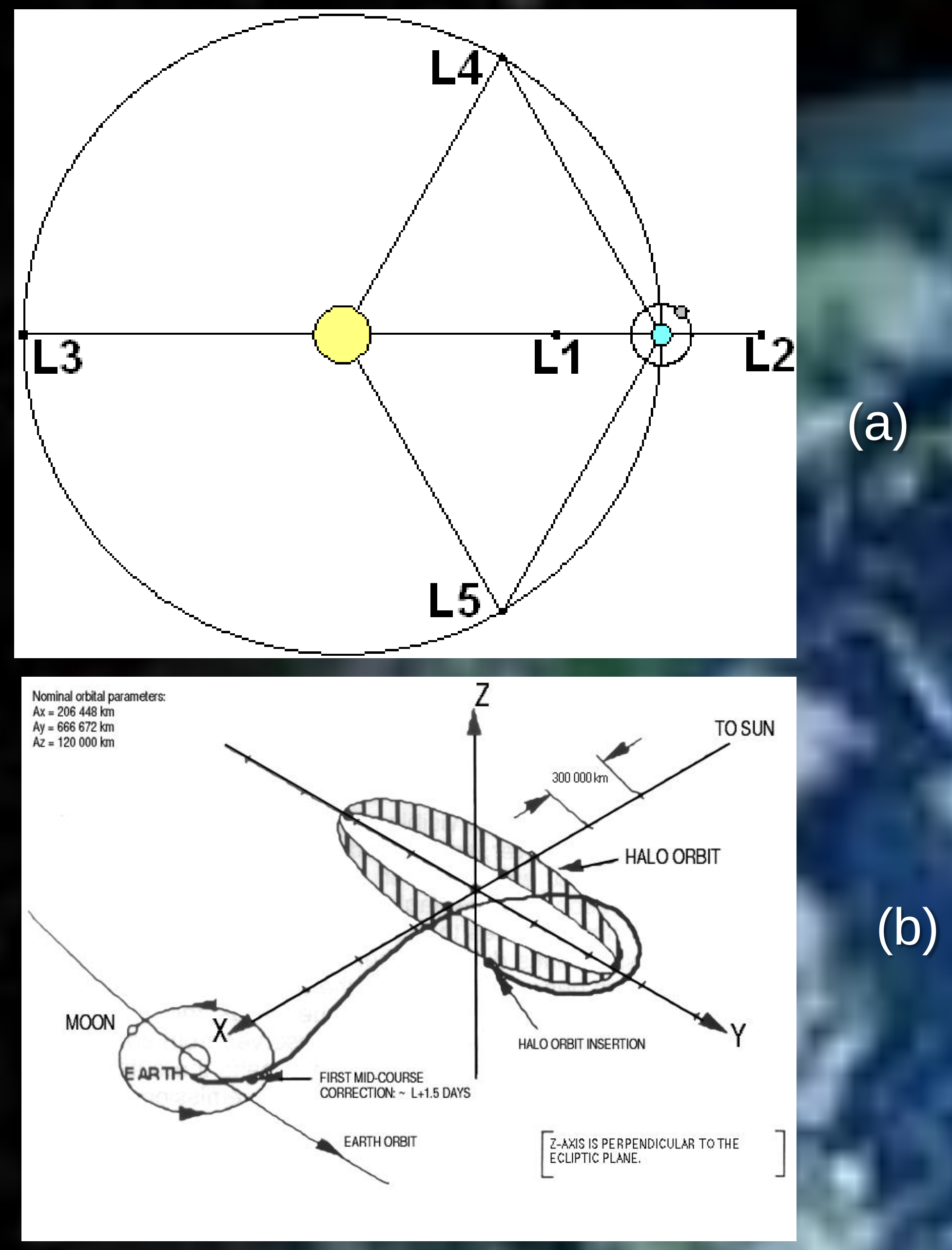


Figure 1: (a) Lagrange points[1] (b) Halo Orbit[2]

GEO Satellite Orbit

The relay satellite will be in Geostationary orbit above the Earth station. Station-keeping at GEO can be done relatively infrequently.

Satellite

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 laser energy beamed from the L1 satellites is 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 93.5dBi. The power will transmit with a beamwidth of 0.0036° which will cause the received beam to be approximately 2.38km 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 6.6% efficiency.

Table 1: Subsystem Efficiencies

Stage	Power Output (MW)	Efficiency
Solar Power	875	1.0
Solar Array	175	0.2
Laser	87.5	0.5
L1 Satellite	**87.5**	**0.25**
Laser PV Receiver	83.125	0.95
Microwave Antenna (DC to RF)	66.5	0.8
GEO Satellite	**66.5**	**0.76**
Rectenna	59.85	0.9
Grid Interface	58.05	0.97
Ground Station	**58.05**	**0.873**
Total System	**58.05**	**0.066**

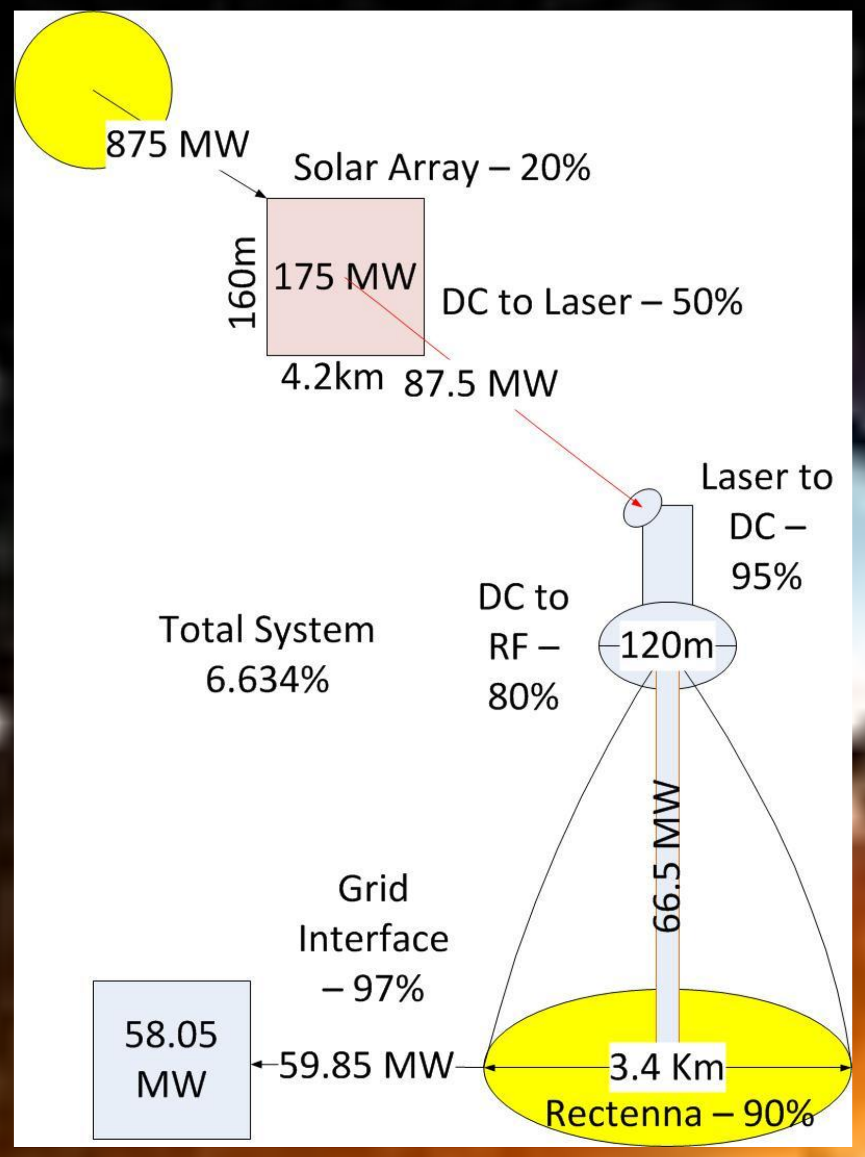


Figure 2: Overall System Efficiency

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 would be used. A 128-bit AES end-to-end encryption with the capability to over the air rekey would 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 $9 km^2$ 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 (0.64λ) in length.

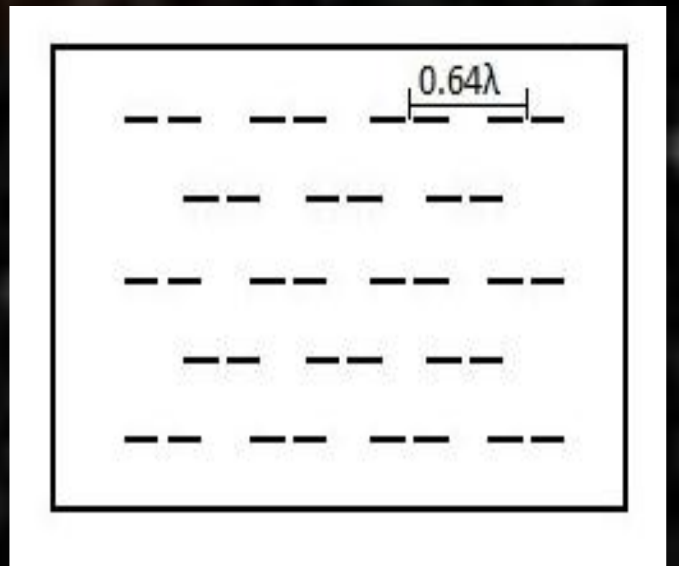


Figure 3: Portion of dipole rectenna array[3]

Budget & Timeline

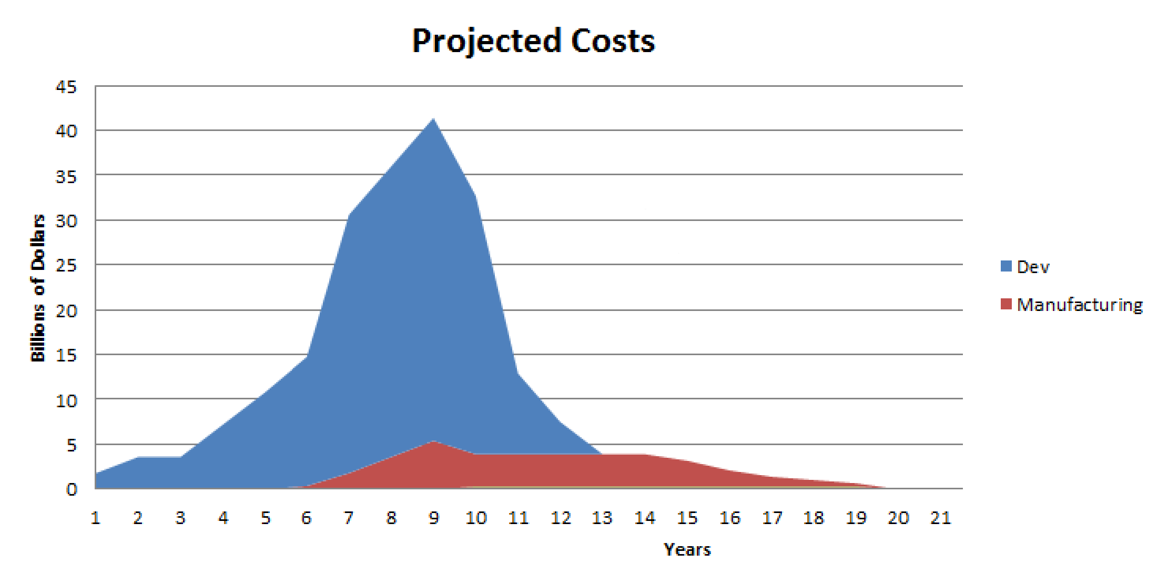


Figure 4: Projected costs

Development prior to deployment will take eight years, with continuing work on software and other challenges through manufacturing and launch. Launches will start after ten years. Each satellite will need three launches, and the cost per kilogram is estimated to be $250/kg for Gen 3. Over the thirty year lifetime of the satellites, operational expenses will total 270 million dollars. The project cost is amortized evenly over the entire 30 years of satellite lifetime. Using a computed value of 790TWh produced, the energy cost is $0.28/kWh. Currently in GA, energy costs about $0.118/kWh and is traded at an average of $35/MWh. Energy cost projects for 2030 (in 2011 dollars) are $119/MWh, giving an estimated consumer energy cost of $0.48/kWh.

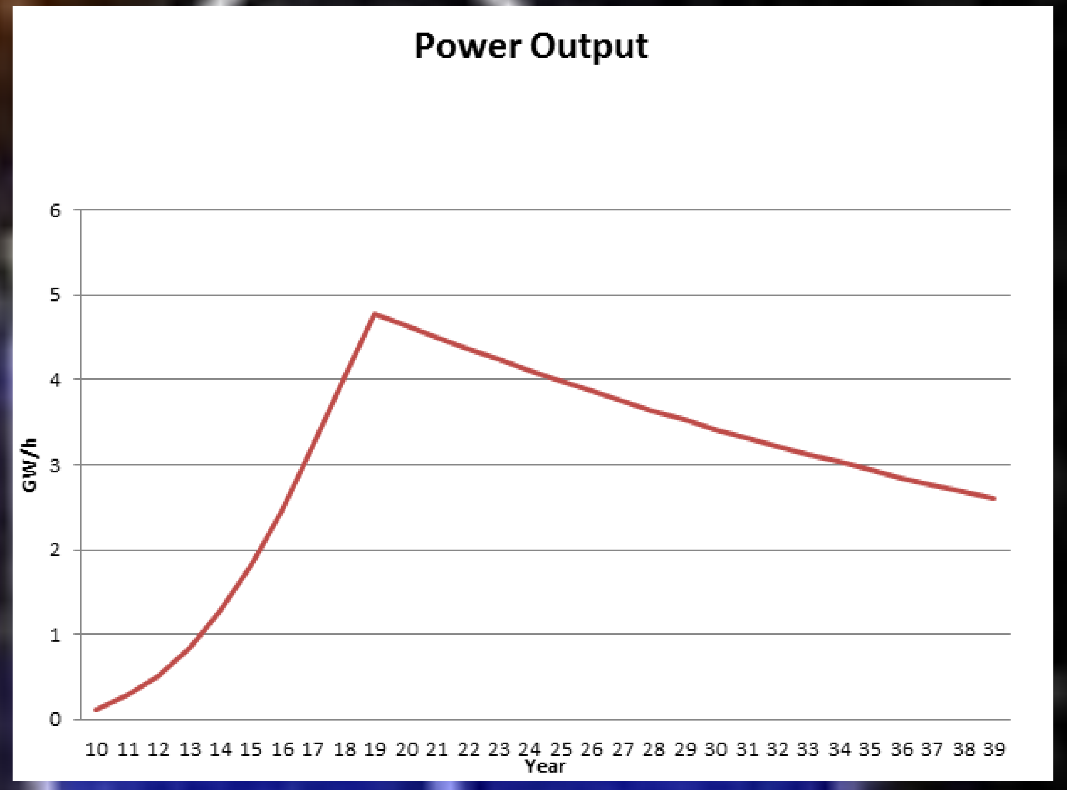


Figure 5: Power delivered to grid

References

[1] E. Pegg, "Manifolds in the Genesis mission," *Math Games*, MAA, Sept 2004. http://www.maa.org
[2] sohowww.nascom.nasa.gov/about/images/halo_orrbit.gif
[3] Adapted from Y. Chun and V. L. Savvin, "Directivity of Multidipole Antennas in Microwave Energy Transmission Systems," *Moscow University Physics Bulletin*, vol. 62, no. 3, pp. 165-169, 2007.

Space Solar Power Design Study

Kelly Miller, Dan Puskas, Alex Dunckle

Van Allen
Electric
Company

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.

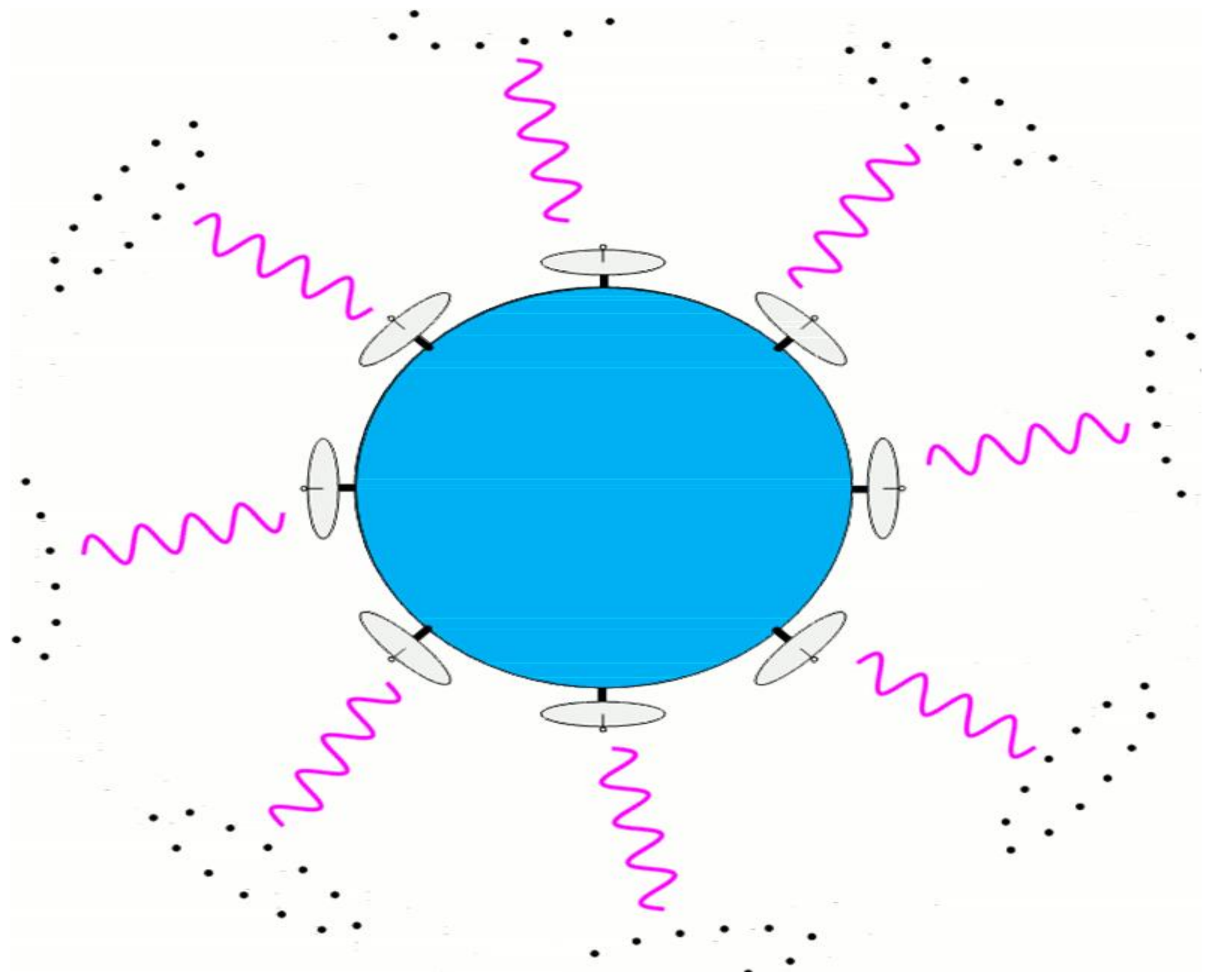


Figure 2. Multiple Satellite Constellation Rings Provide Continuous Coverage to Rectenna Sites Worldwide.

References

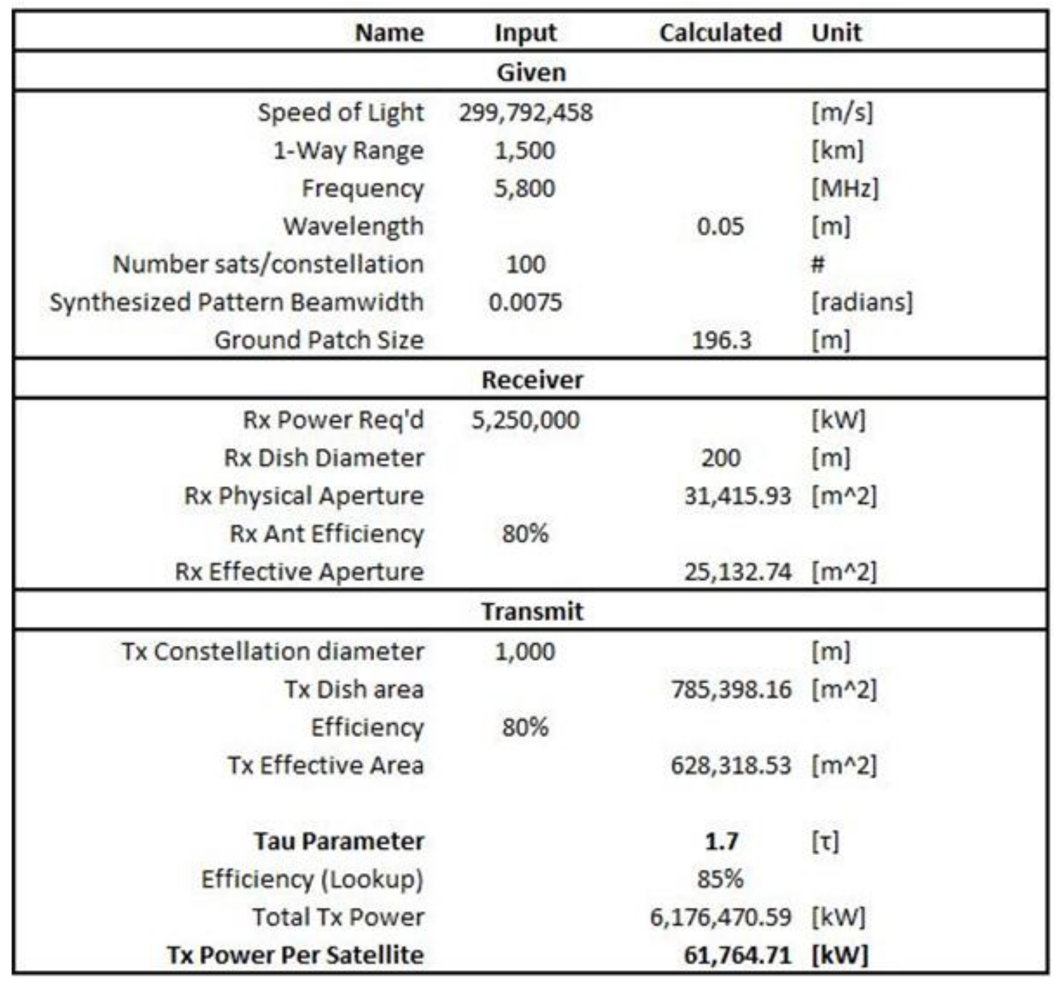
Brown, William C. "Beamed Microwave Power Transmission and its Application to Space". IEEE Trans on Microwave Theory and Techniques. 1992.

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

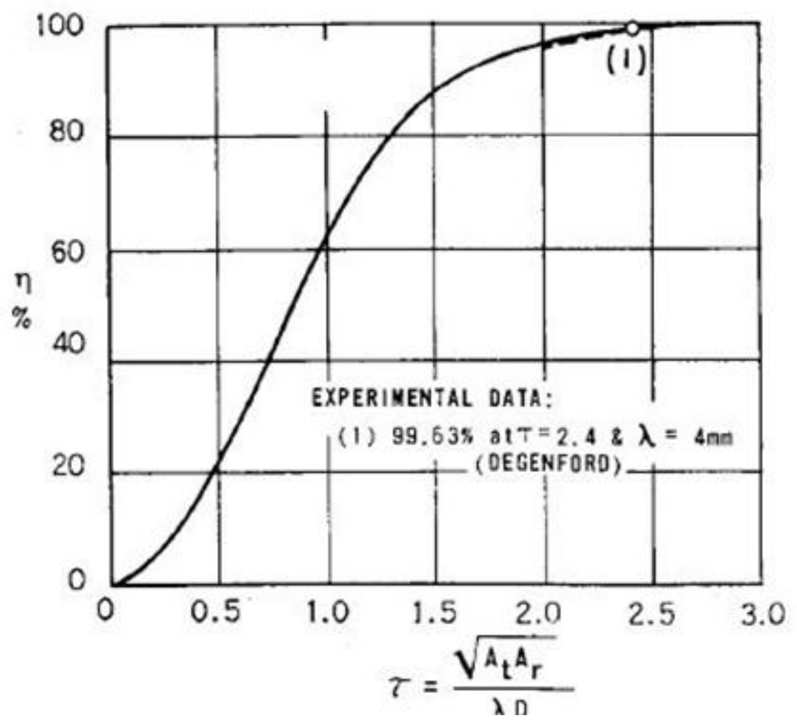
Aurora Borealis Image. Internet: http://www.blogenius.com/northern-lights-travel-south-aurora-borealis-seen-in-over-20-states-photos/ [12/15/2011]

Patch antenna. Internet: http://media.digikey.com/Photos/Taoglas/MFG_GP_25B.jpg [12/15/2011]

Pratt, Bostian, and Allnutt. "Satellite Communications, 2nd edition". Wiley, 2003



Name	Input	Calculated	Unit
Given			
Speed of Light	299,792,458		[m/s]
1-Way Range	1,500		[km]
Frequency	5,800		[MHz]
Wavelength		0.05	[m]
Number sats/constellation	100		#
Synthesized Pattern Beamwidth	0.0075		[radians]
Ground Patch Size		196.3	[m]
Receiver			
Rx Power Req'd	5,250,000		[kW]
Rx Dish Diameter		200	[m]
Rx Physical Aperture		31,415.93	[m^2]
Rx Ant Efficiency	80%		
Rx Effective Aperture		25,132.74	[m^2]
Transmit			
Tx Constellation diameter	1,000		[m]
Tx Dish area		785,398.16	[m^2]
Efficiency	80%		
Tx Effective Area		628,318.53	[m^2]
Tau Parameter		**1.7**	[τ]
Efficiency (Lookup)		85%	
Total Tx Power		6,176,470.59	[kW]
Tx Power Per Satellite		**61,764.71**	**[kW]**



$$\tau = \frac{\sqrt{A_t A_r}}{\lambda D}$$

Figure 3. Large Space Constellation Allows for Focused Energy on Earth, Minimizing Satellite and Rectenna Sizes

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.

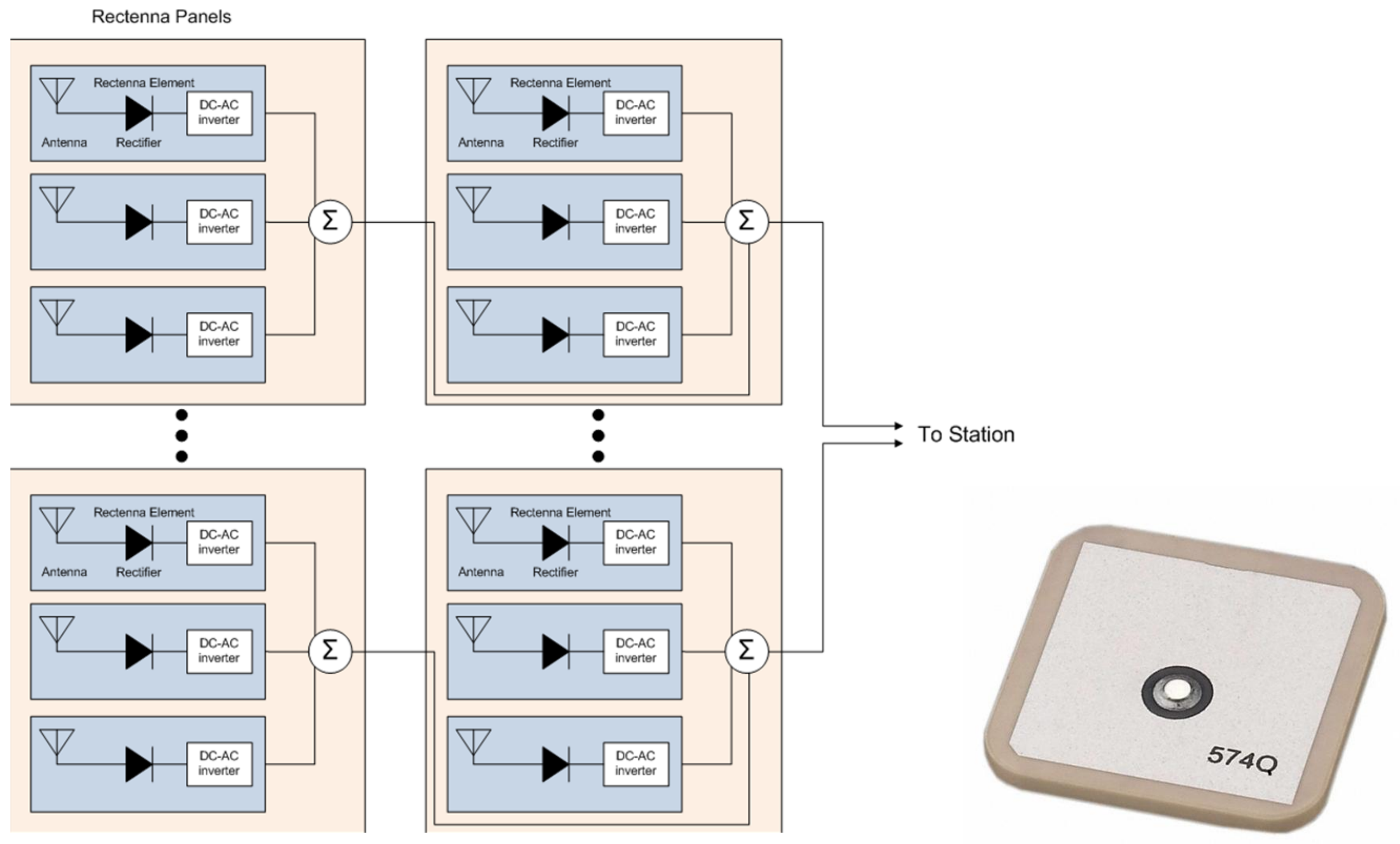
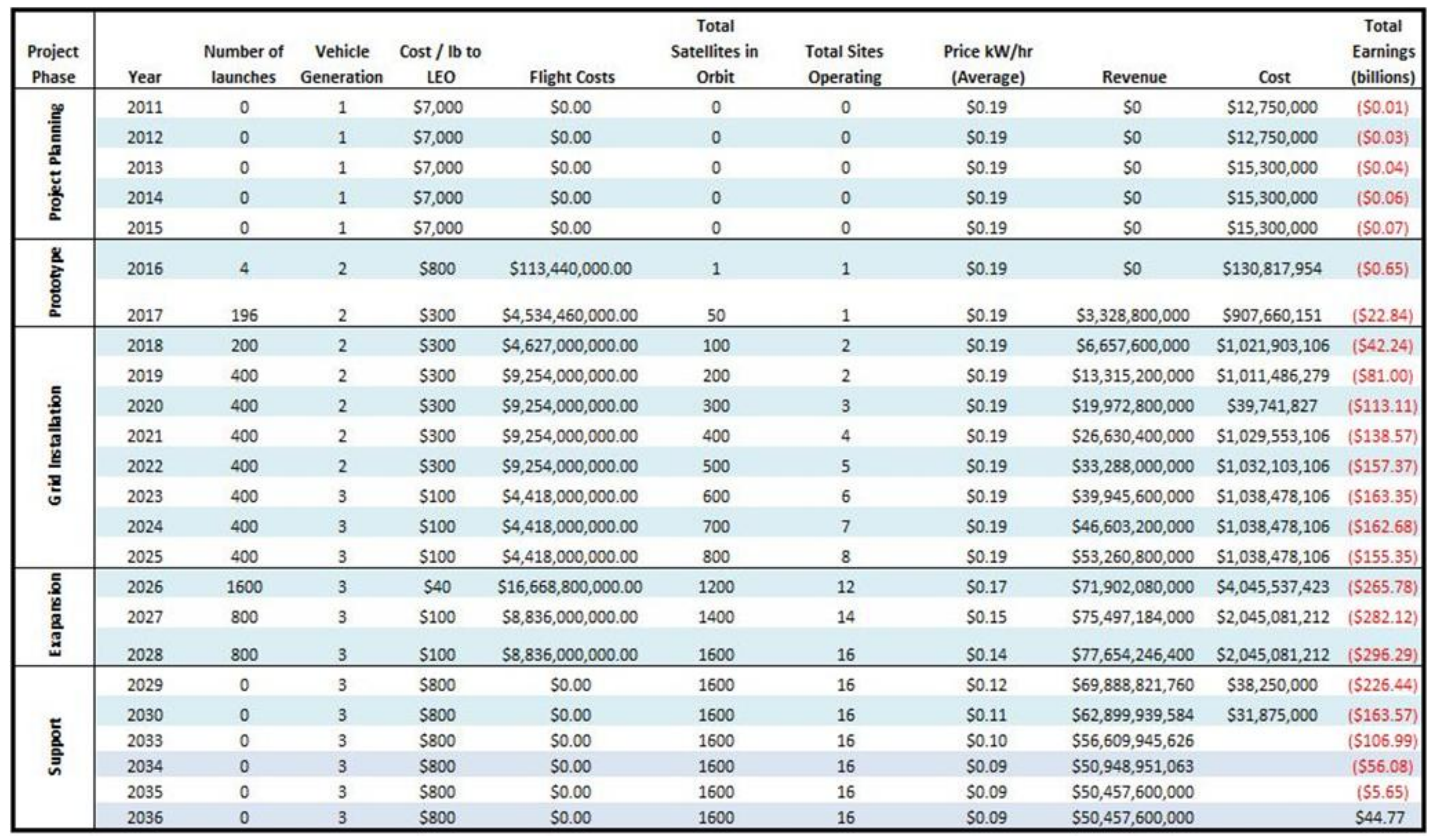


Figure 4. Rectenna design employs patch antennas for an economical method to build a large rectenna aperture.

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.



Project Phase	Year	Number of launches	Vehicle Generation	Cost / lb to LEO	Flight Costs	Total Satellites in Orbit	Total Sites Operating	Price kW/hr (Average)	Revenue	Cost	Total Earnings (billions)
Project Planning	2011	0	1	$7,000	$0.00	0	0	$0.19	$0	$12,750,000	($0.01)
	2012	0	1	$7,000	$0.00	0	0	$0.19	$0	$12,750,000	($0.03)
	2013	0	1	$7,000	$0.00	0	0	$0.19	$0	$15,300,000	($0.04)
	2014	0	1	$7,000	$0.00	0	0	$0.19	$0	$15,300,000	($0.06)
	2015	0	1	$7,000	$0.00	0	0	$0.19	$0	$15,300,000	($0.07)
Prototype	2016	4	2	$800	$113,440,000.00	1	1	$0.19	$0	$130,817,954	($0.65)
	2017	196	2	$300	$4,534,460,000.00	50	1	$0.19	$3,328,800,000	$907,660,151	($22.84)
Grid Installation	2018	200	2	$300	$4,627,000,000.00	100	2	$0.19	$6,657,600,000	$1,021,903,106	($42.24)
	2019	400	2	$300	$9,254,000,000.00	200	2	$0.19	$13,315,200,000	$1,011,486,279	($81.00)
	2020	400	2	$300	$9,254,000,000.00	300	3	$0.19	$19,972,800,000	$39,741,827	($113.11)
	2021	400	2	$300	$9,254,000,000.00	400	4	$0.19	$26,630,400,000	$1,029,553,106	($138.57)
	2022	400	2	$300	$9,254,000,000.00	500	5	$0.19	$33,288,000,000	$1,032,103,106	($157.37)
	2023	400	3	$100	$4,418,000,000.00	600	6	$0.19	$39,945,600,000	$1,038,478,106	($163.35)
	2024	400	3	$100	$4,418,000,000.00	700	7	$0.19	$46,603,200,000	$1,038,478,106	($162.68)
	2025	400	3	$100	$4,418,000,000.00	800	8	$0.19	$53,260,800,000	$1,038,478,106	($155.35)
Exapansion	2026	1600	3	$40	$16,668,800,000.00	1200	12	$0.17	$71,902,080,000	$4,045,537,423	($265.78)
	2027	800	3	$100	$8,836,000,000.00	1400	14	$0.15	$75,497,184,000	$2,045,081,212	($282.12)
	2028	800	3	$100	$8,836,000,000.00	1600	16	$0.14	$77,654,246,400	$2,045,081,212	($296.29)
Support	2029	0	3	$800	$0.00	1600	16	$0.12	$69,888,821,760	$38,250,000	($226.44)
	2030	0	3	$800	$0.00	1600	16	$0.11	$62,899,939,584	$31,875,000	($163.57)
	2033	0	3	$800	$0.00	1600	16	$0.10	$56,609,945,626		($106.99)
	2034	0	3	$800	$0.00	1600	16	$0.09	$50,948,951,063		($56.08)
	2035	0	3	$800	$0.00	1600	16	$0.09	$50,457,600,000		($5.65)
	2036	0	3	$800	$0.00	1600	16	$0.09	$50,457,600,000		$44.77

Figure 5. Launching Many Satellites Allows for Reduced Cost and Full Return on Investment by 2036.

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.

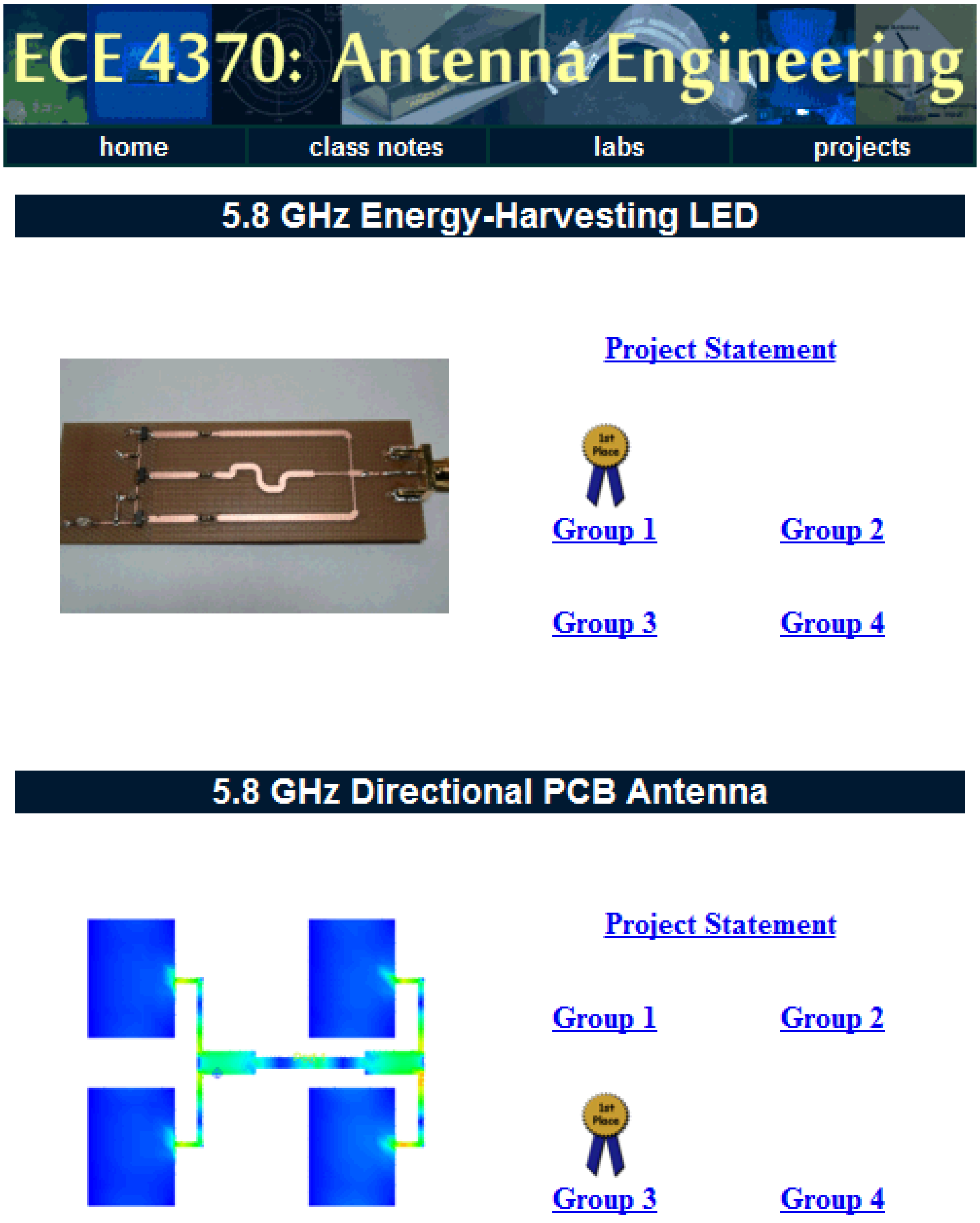
2011 Microwave Power Transfer Symposium

Thursday, 15 December 2011, 3-6pm, MiRC 102 Georgia Tech Campus

"Shooting for the Stars"

Posters for ECE 4370 Project Teams

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



ECE 4370: Antenna Engineering

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

$$Z_0 = \frac{120\pi h}{W\sqrt{\varepsilon_{\text{eff}}}}$$

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{12h}{W}\right)^{-1/2}$$

$$\Delta l = 0.412h\left(\frac{\varepsilon_{\text{eff}} + 0.3}{\varepsilon_{\text{eff}} - 0.258}\right)\frac{(W/h) + 0.264}{(W/h) + 0.8}$$

$$f_r = \frac{c}{2\sqrt{\varepsilon_{\text{eff}}}(L + 2\,\Delta l)}$$

Antenna Design Process

- The antenna was built with copper tape on a PCB
- Slight adjustments were made to the copper tape dimensions in order to fine tune the antenna to 5.8 GHz and a suitable input impedance
- The antenna is center-fed, which eliminates the interaction between the radiation from the antenna's edges and the feed system
- After testing with the network analyzer, the return loss was determined to be -27 dB at 5.8 GHz
- The bandwidth was determined to be approximately 500 MHz
- The input impedance was almost perfectly matched to 50 ohms

Final Antenna Design

Front

Back

Charge Pump Design

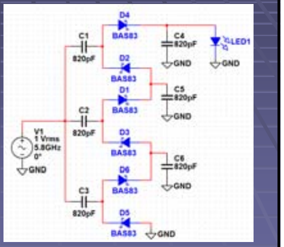
- The charge pump must take a 5.8 GHz signal from the antenna as input
- The signal must be converted to a DC signal of necessary power to light an LED
- The charge pump must be matched to 50 ohms
- Consists of SOT-323 package RF Schottky Diodes, an L62705CT-ND LED, and 820 pF capacitors

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

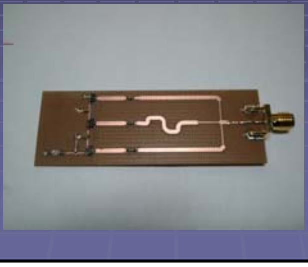
Charge Pump Design Process

- 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.



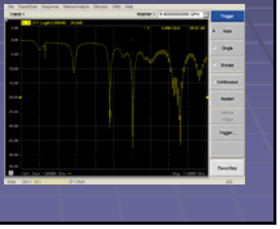
Final Charge Pump Design

- 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.

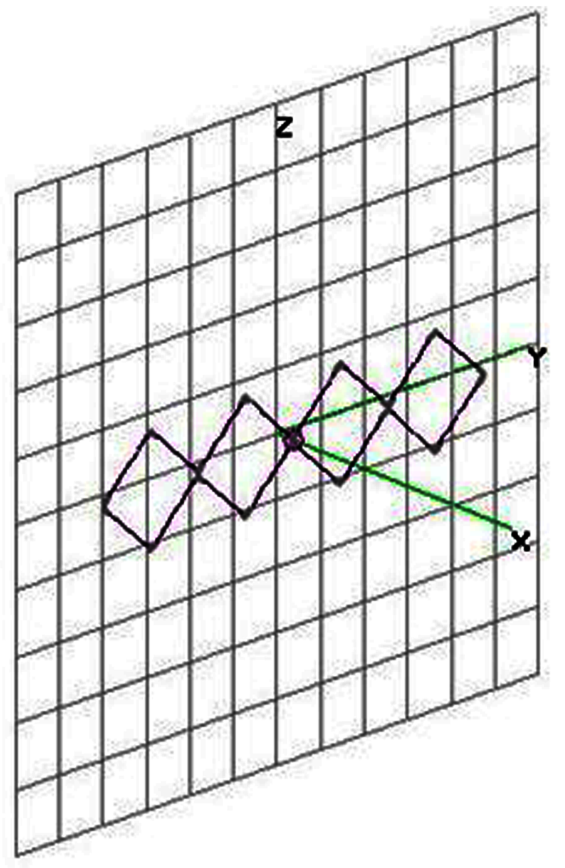
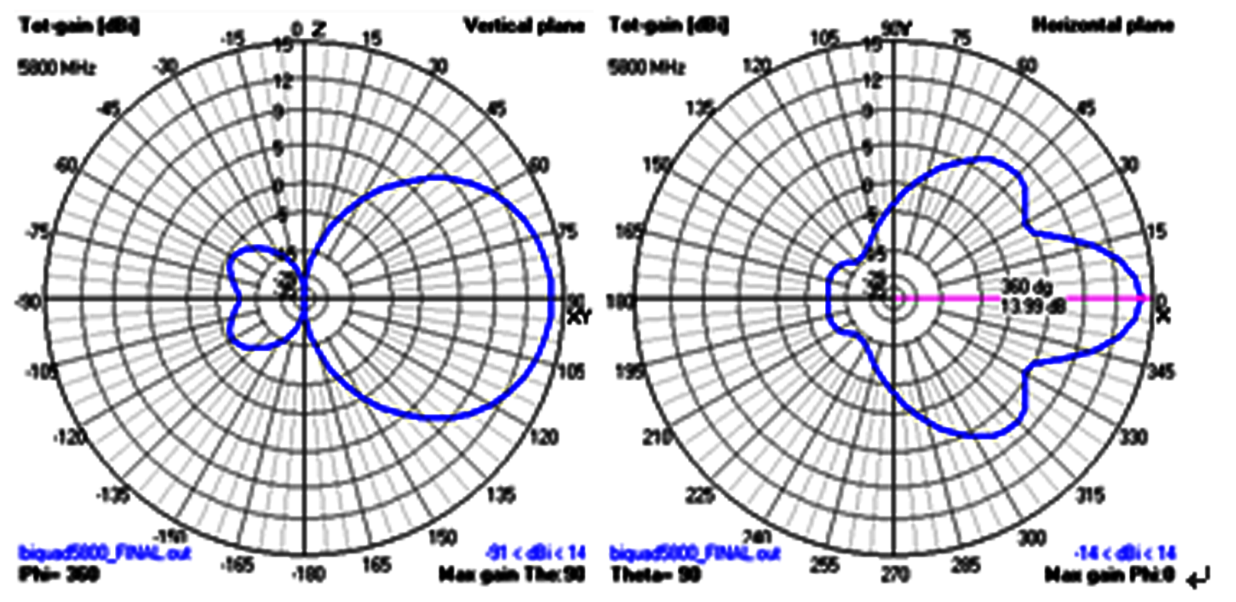


Figure 1. Double bi-quad antenna constructed in NEC.

Elements:

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



(a) vertical plane (b) horizontal plane

Figure 2. Simulation of double bi-quad antenna pattern.

Simulation:

- 5.8GHz
- 14 dBi peak gain
- 4.6 + j8.6 ohms impendence

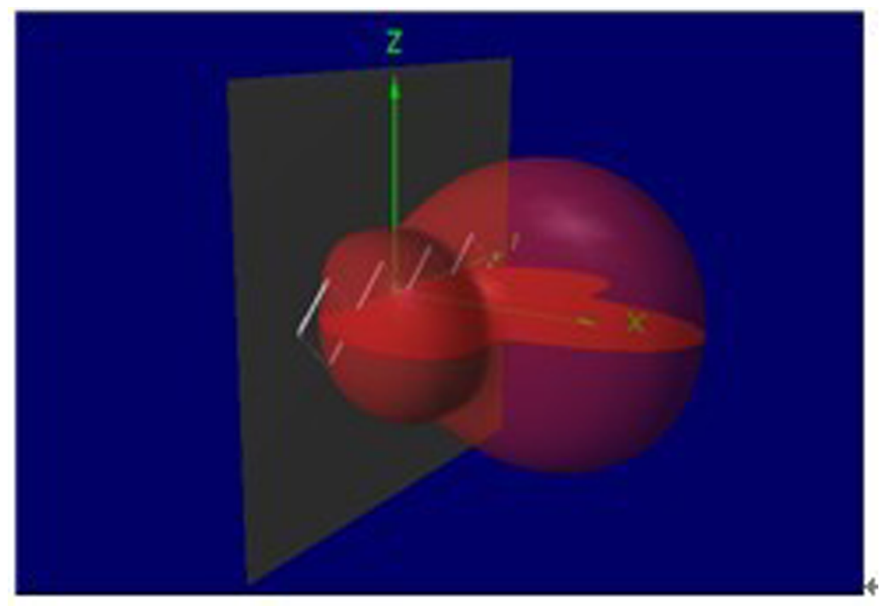
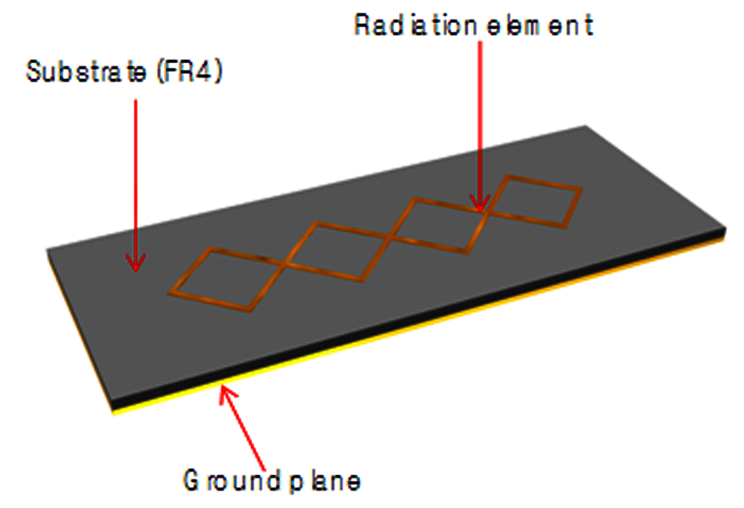


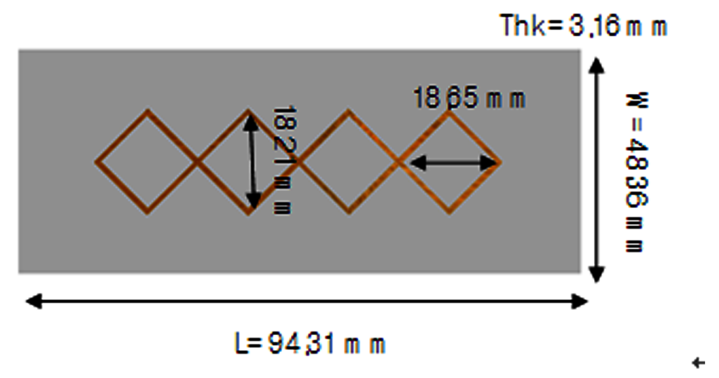
Figure 3. 3D model of double bi-quad antenna with overlayed 3D radiation pattern in NEC.

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.

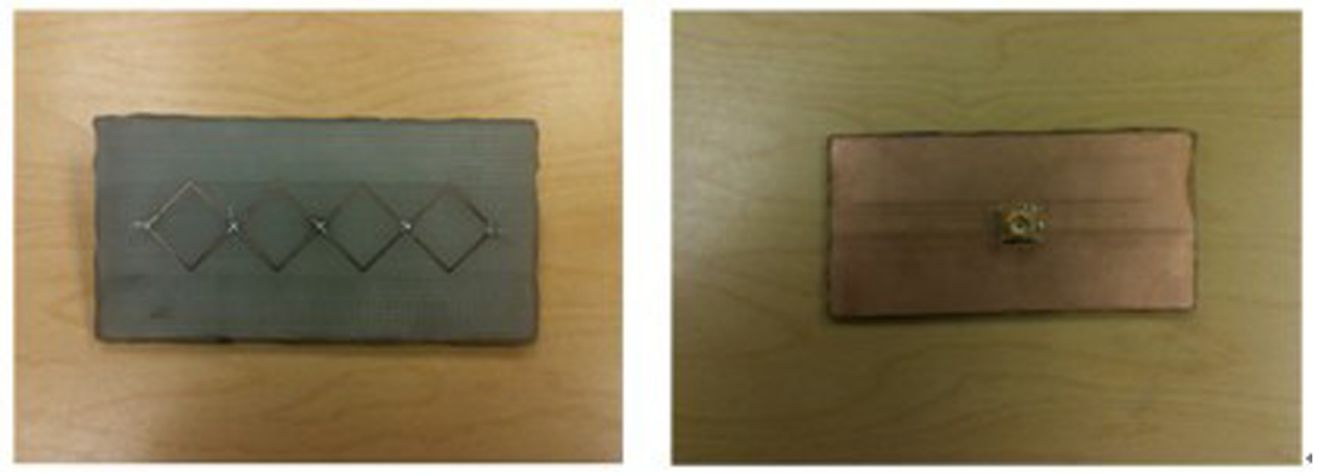


(a) 3D view



(b) Top view

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



(a) Front side (b) Back side

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

Experiment & Result

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

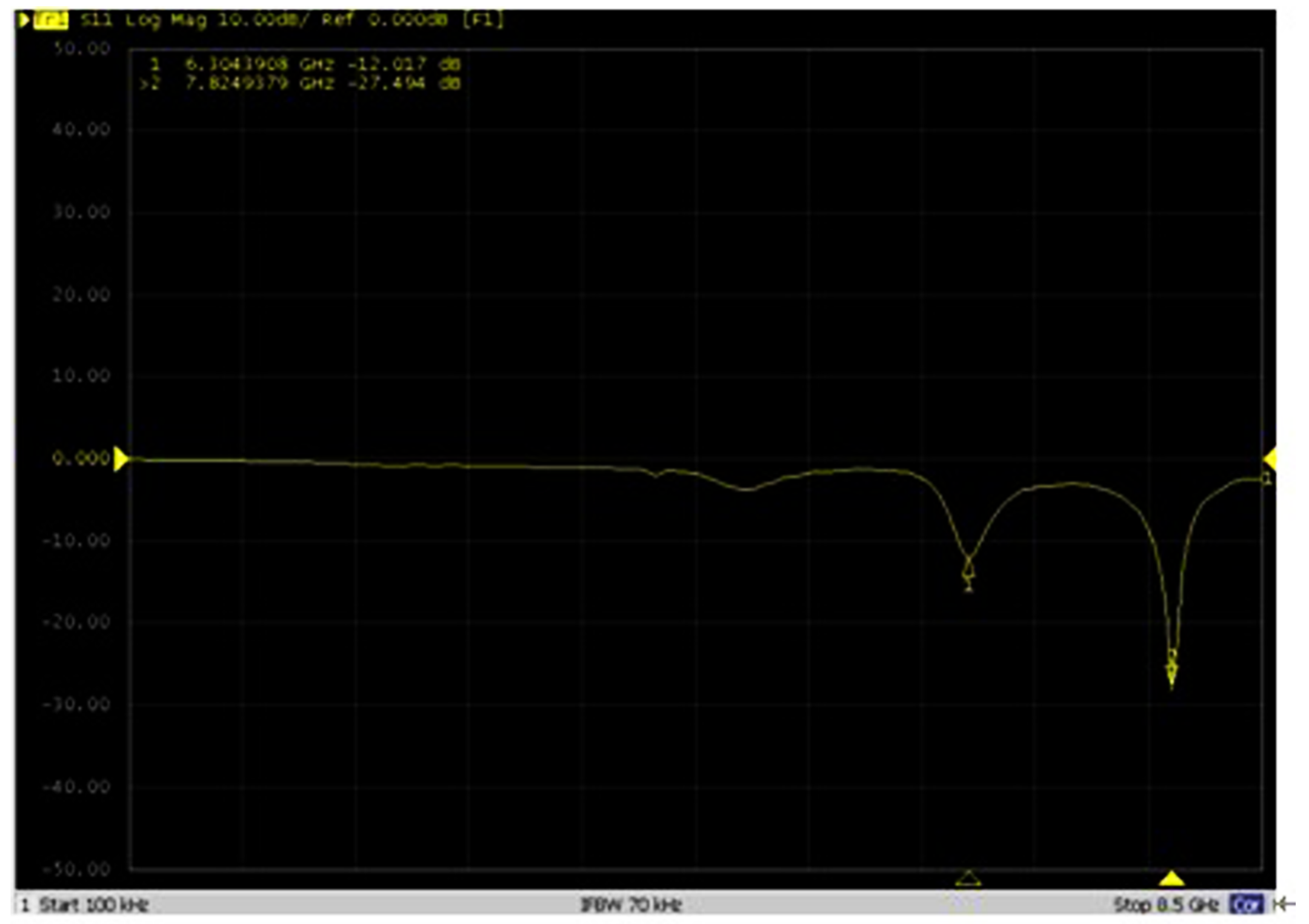


Figure 8. Return loss (S11 parameter) of the antenna measured with network analyzer.
Return loss (S11 parameter) ----- 6.30GHz and 7.82GHz

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.

Patch Antenna Array for an RF Energy Harvesting Circuit at 5.8 GHz

Matthew Campbell, Mark Ficker, Stefan Lepkowski, Max Liao

Georgia Institute of Technology,

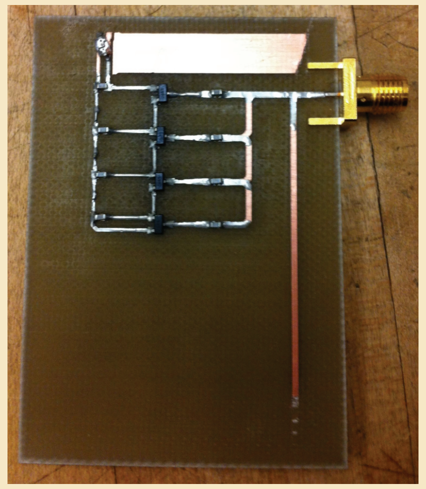
Introduction

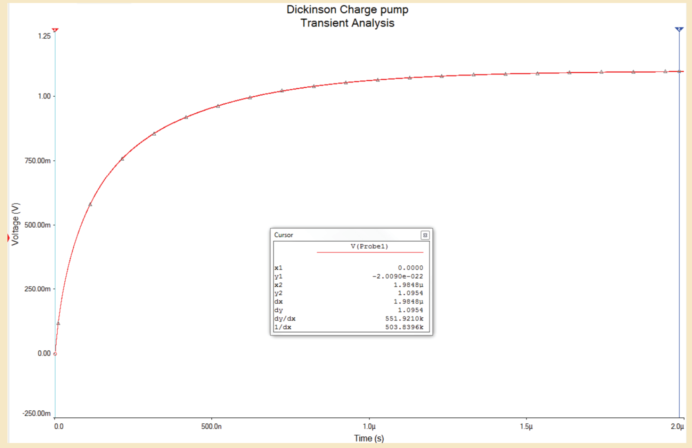
RF energy is constantly being transmitted in modern environments. This energy typically goes to waste when no receivers are present to pick up the signal. A microwave charge pump can be used to gather this energy and convert it into a low-leveled power supply. An array of antennas provides a continuous 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 energy harvester and patch antennas will be constructed separately and the two devices will be interfaced with a 50 Ω SMA transmission line. In this design, 4 patch antennas will be used as the receiver and a 4-stage charge pump will provide power to the LED.

Energy Harvester

A Dickson charge pump was designed at a frequency of 5.8 GHz for use in an energy harvesting circuit. The charge pump uses a combination of diodes and capacitors to convert the source signal from the antennas into a DC voltage. This voltage is applied across a capacitor and the load in parallel. The capacitor will charge up over time (as seen in the transient analysis below) and the LED can be lit with a 10 dBm continuous input.

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

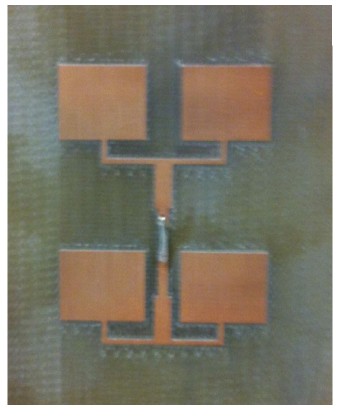


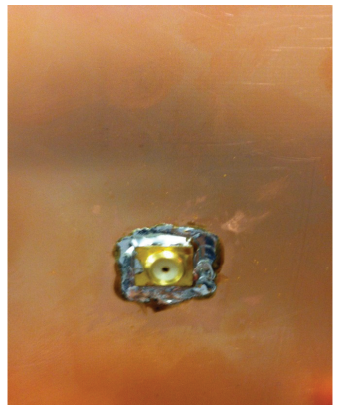


```
V(Probe1)
x1          0.0000
y1   -2.0090e-022
x2         1.9848µ
y2          1.0954
dx         1.9848µ
dy          1.0954
dy/dx    551.9210k
1/dx     503.8396k
```

Patch

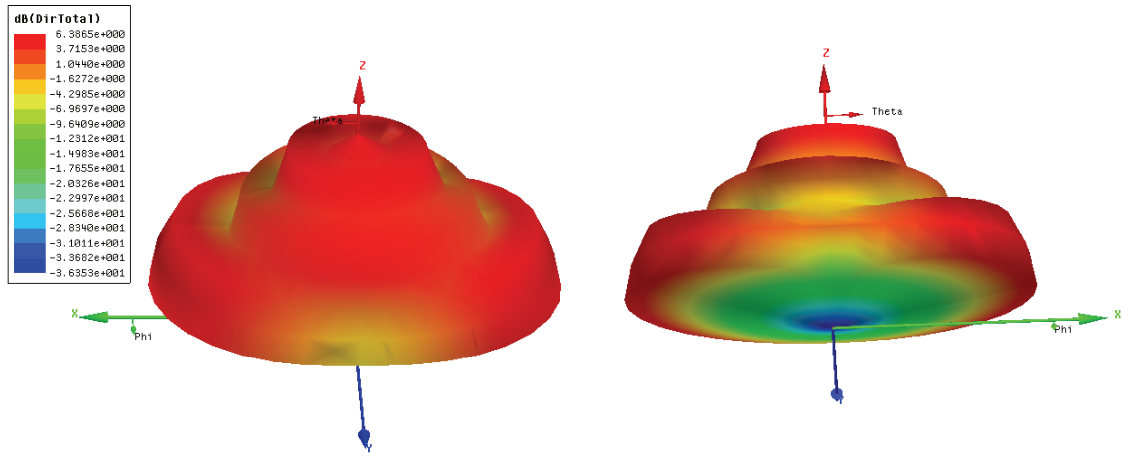
The antennas to be used in this design are patch antennas. Patch antennas have advantages as they are not only cheap and easy to fabricate but also versatile in terms of resonant frequency, polarization, pattern, impedance, and conformability to planar and non-planar surfaces. They can also easily be 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. An 50 Ω SMA connection was soldered at the halfway point along the central microstrip line.



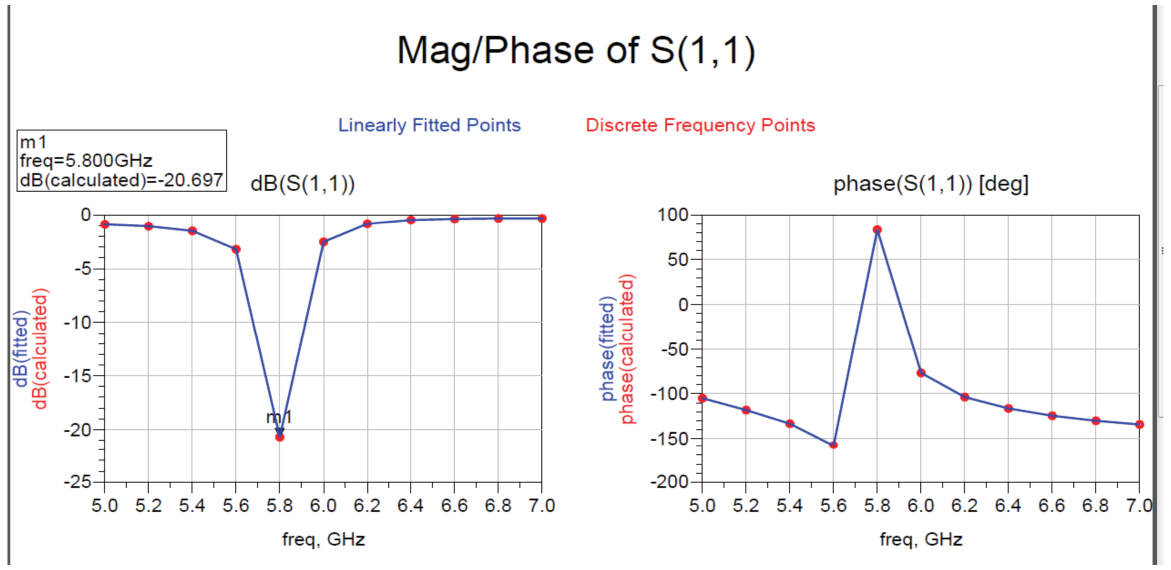


The optimization performed was mostly comprised of the microstrip matching network used to feed the multiple patch antennas. Both the antenna and the microstrip are printed using copper. When placing the antennas in an array, the matching network is incredibly important in keeping the impedances matched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

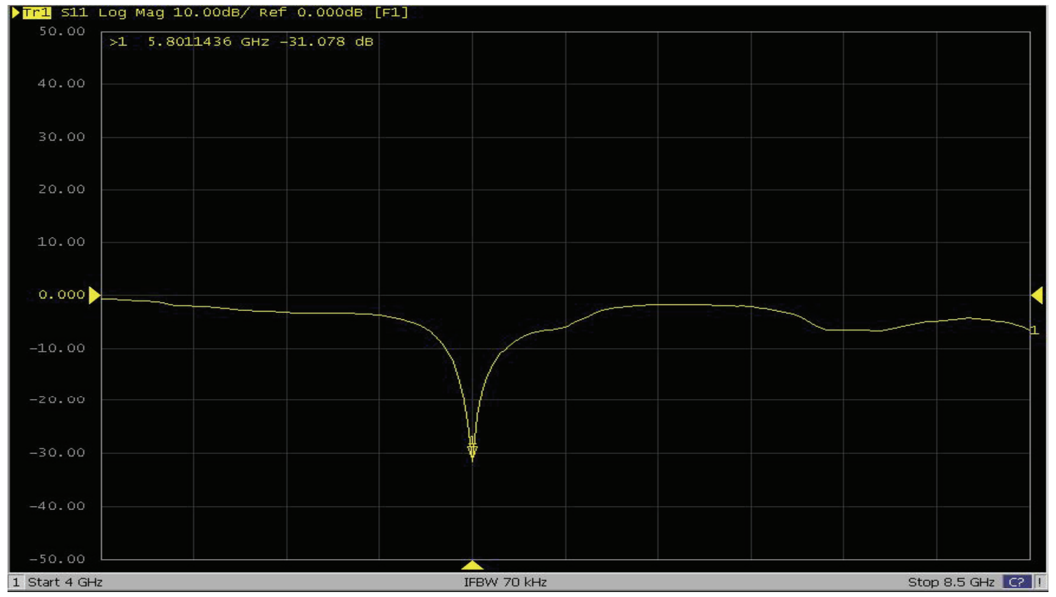
A simulation was performed on a single patch antenna in HFSS and its directivity is plotted in dB. An infinite ground plane was placed 1.5 mm underneath the antenna in order to increase our peak gains. There are nulls at the origin because of this ground plane and a maximum peak of in the z+ direction.



Simulations/Results

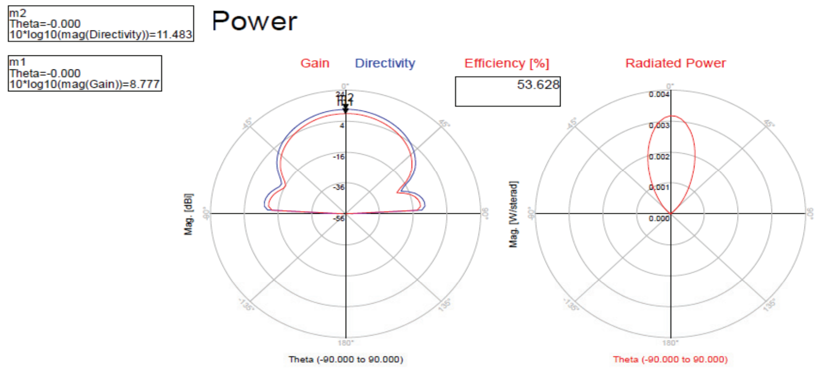


The antenna design was simulated in ADS which graphically displays the S11 in dB. At the resonant frequency of 5.8 GHz, the maximum power is being received.The simulation in the figure above shows a minimum of -20.7 dB at the operating frequency. A network analyzer was used to measure the same parameter after the antenna was milled. The results show a minimum s11 of -31dB.



```
Tr1 S11 Log Mag 10.00dB/ Ref 0.000dB [F1]
>1   5.8011436 GHz -31.078 dB
1 Start 4 GHz                IFBW 70 kHz                Stop 8.5 GHz C? !
```

The gain for our antenna array is simulated in ADS and ploted in a polar graph displayed. This simulation shows that the array radiates with a peak gain of 8.777 dB in the +z direction.



5.8GHz RF Energy Harvester

Khai Ha, Colin Pardue, Jack Song, Michael Coulter

Georgia Institute of Technology, Atlanta, GA

Georgia Tech Electrical and Computer Engineering

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.

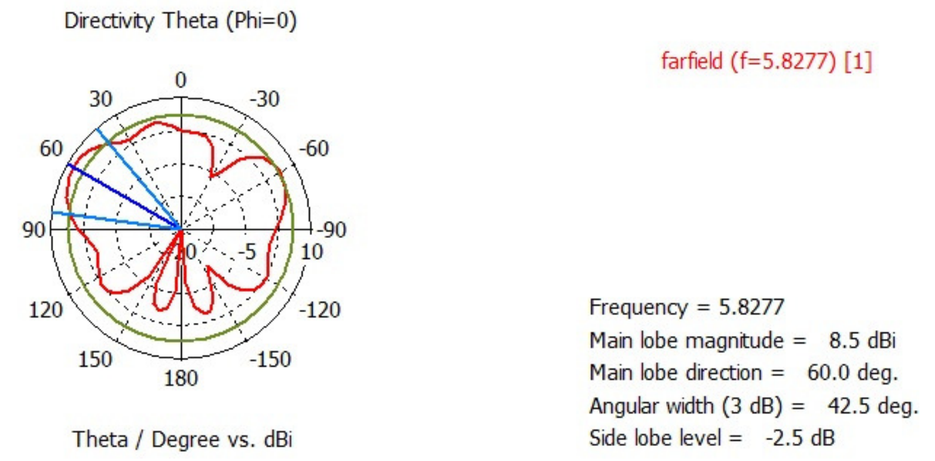


Figure 7: Antenna gain simulation.

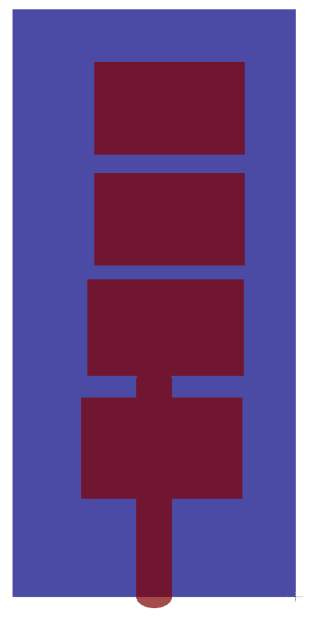


Figure 1: Patch Antenna Array design

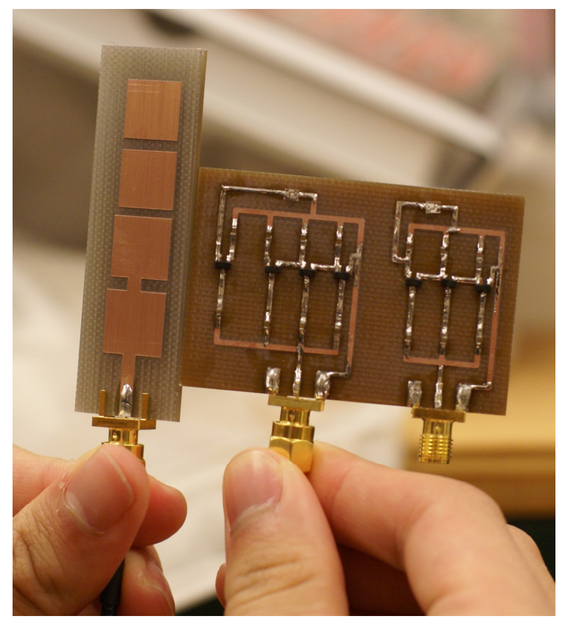


Figure 2: The realized patch antenna array (left)

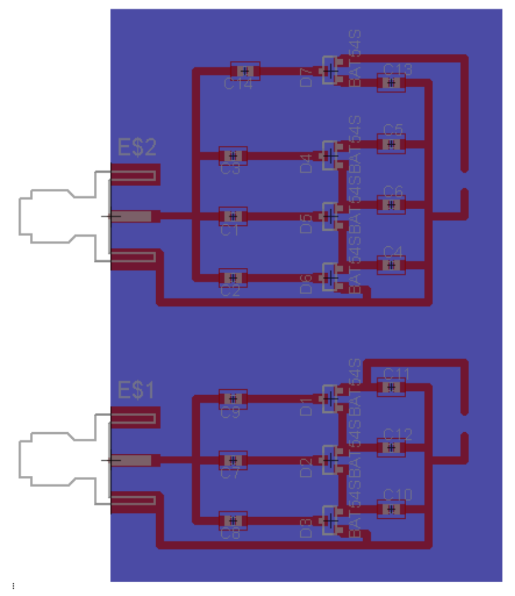


Figure 3: 3 and 4 Stage Charge Pump Designs.

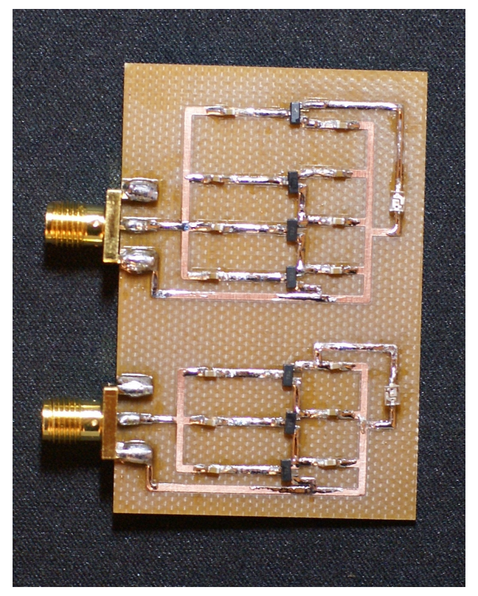


Figure 4: The realized 3 and 4 stage Charge Pumps

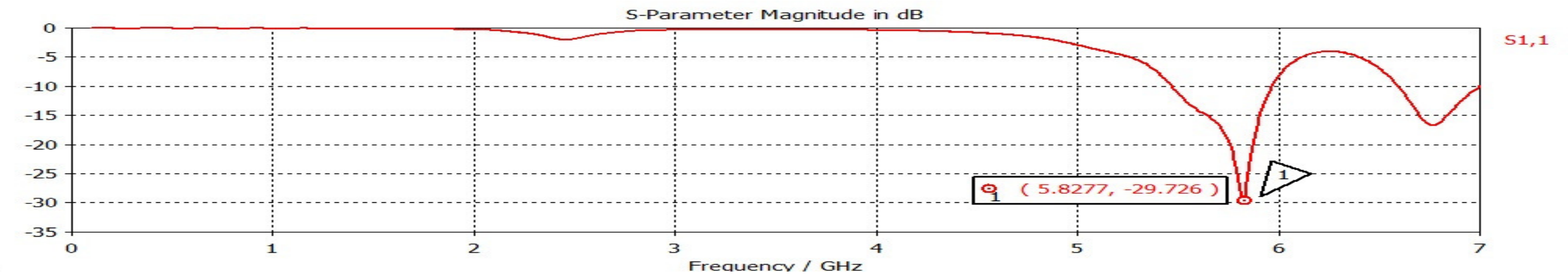
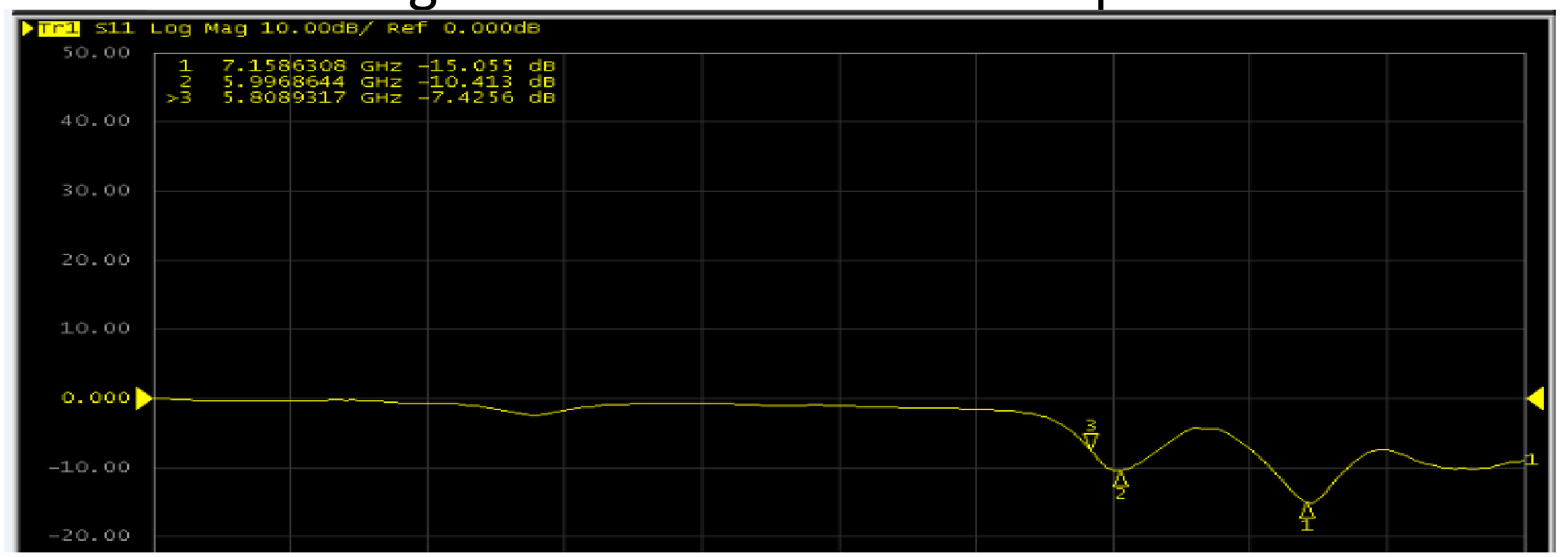


Figure 5: The simulated S11 parameters.



```
Tr1 S11 Log Mag 10.00dB/ Ref 0.000dB
  1   7.1586308 GHz -15.055 dB
  2   5.9968644 GHz -10.413 dB
 >3   5.8089317 GHz -7.4256 dB
```

Figure 6: The actual S11 parameters.

The charge pump design chosen was a classic and simple design that was easily fabricated and populated with the RF schottky diodes (AV02-1388EN), the LED (CMD28-21), and the 850pF capacitors (C06BLBB2X5). Soldering was done by hand.

Results

The antenna (figure 2), with the dimensions

$$\text{width} := \left(\frac{2}{e_r + 1}\right)^{\frac{1}{2}} \cdot \frac{c}{2\cdot\left(f_r\right)}.$$

$$e_{\text{effective}} := \frac{\left(e_r + 1\right)}{2} + \frac{\left(e_r - 1\right)}{2}\cdot\left(1 + 12\cdot\frac{h}{\text{width}}\right)^{(-.5)}$$

$$\text{deltaL} := h\cdot .412\cdot\left[\frac{\left(e_{\text{effective}} + .3\right)\cdot\left(\frac{\text{width}}{h} + .264\right)}{\left(e_{\text{effective}} - .258\right)\cdot\left(\frac{\text{width}}{h} + .8\right)}\right]$$

$$\text{length} := \frac{c\cdot 100}{2\cdot f_r\cdot\left(e_{\text{effective}}\right)^{.5}} - 2\cdot\text{deltaL}$$

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.

Slides for Keynote Speech

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

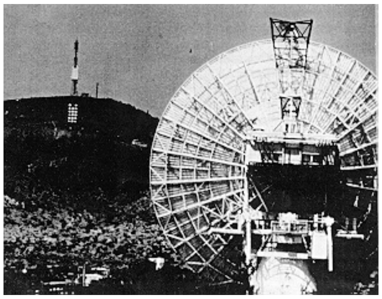
- Tesla Experiments with standing wave
- Magnetron tube development
- Rectenna development
    - William Brown at Raytheon
- Laser

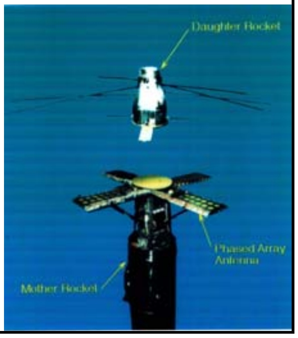
Background continued

> *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 I 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 CO_2 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*

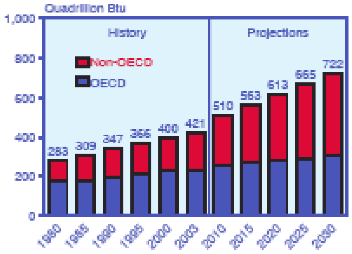


Figure 1. World Marketed Energy Consumption by Region, 1980-2030

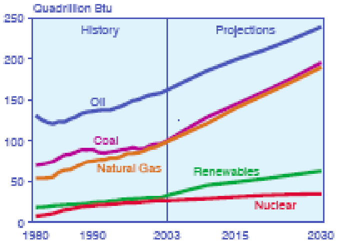
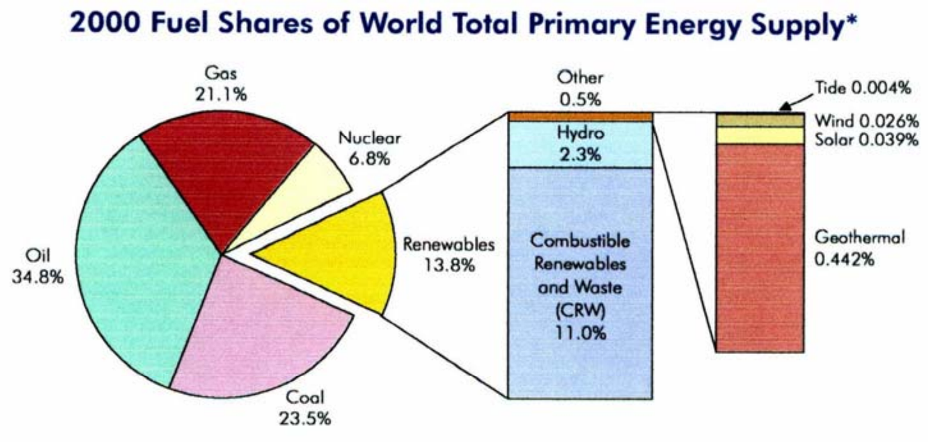


Figure 3. World Marketed Energy Use by Energy Type, 1980-2030

* From US Department of Energy Energy Information Agency
“International Energy Outlook 2006”



2000 Fuel Shares of World Total Primary Energy Supply*

International Energy Agency "Renewables in Global Energy Supply", an IEA fact sheet

Economic development linked to energy — slight improvement in efficiency

Figure 20. World Gross Domestic Product in Three Economic Growth Cases, 1970-2020

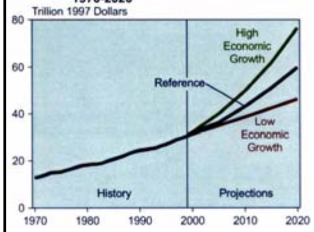


Figure 21. World Energy Consumption in Three Economic Growth Cases, 1970-2020

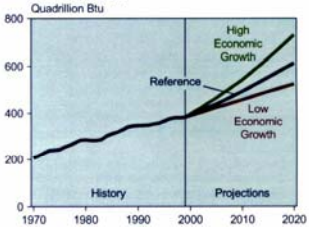
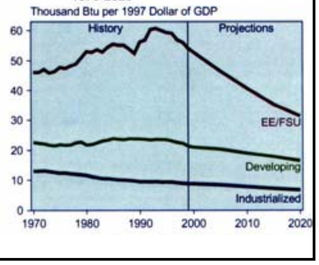


Figure 22. World Energy Intensity by Region, 1970-2020



* From US Department of Energy Energy Information Agency "International Energy Outlook 2002"

Electric Power

Figure 55. World Net Electricity Consumption, 2003-2030

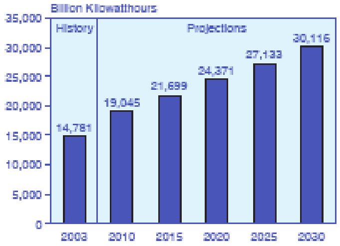


Figure 56. World Net Electricity Consumption by Region, 1980-2030

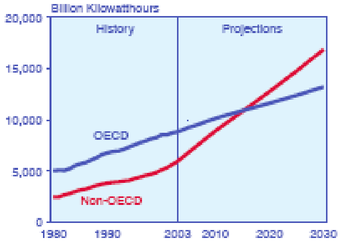


Figure 58. Net Electricity Consumption in Non-OECD Countries by End-Use Sector, 2003, 2015, and 2030

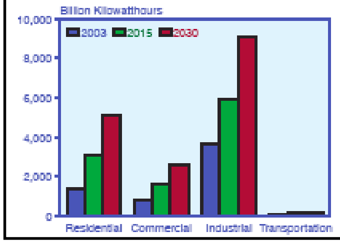
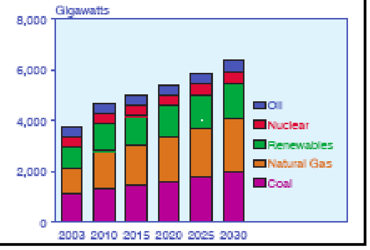
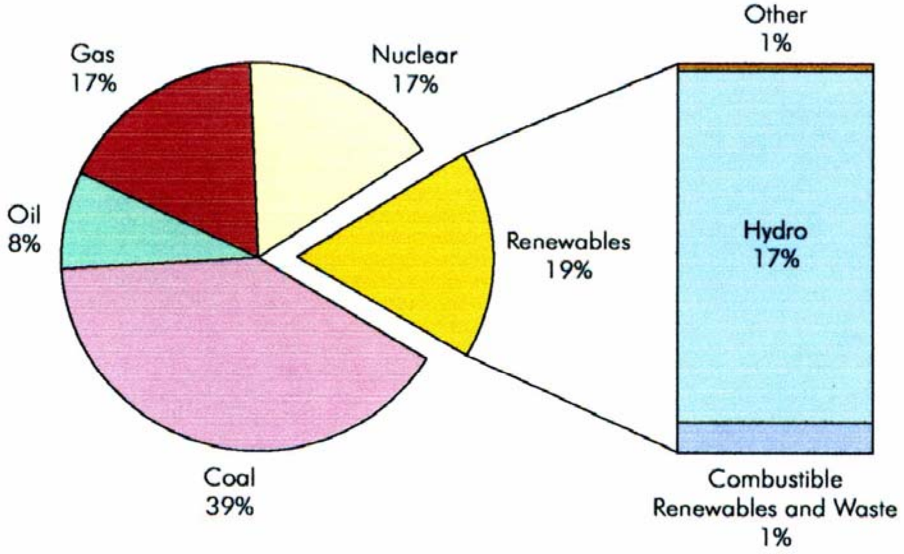


Figure 59. World Electricity Generating Capacity by Fuel Type, 2003-2030



Renewables in Electricity Production

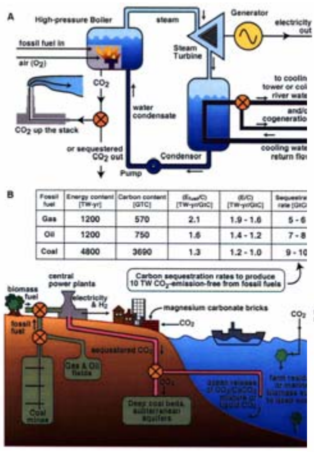


International Energy Agency "Renewables in Global Energy Supply", an IEA fact sheet

Alternative Carbon Neutral Strategies

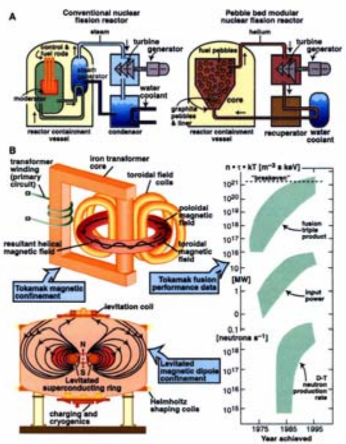
Terrestrial Solar

CO$_2$ Sequestration



Fossil fuel	Energy content [TW-yr]	Carbon content [GTC]	(E_{fuel}/C) [TW-yr/GtC]	(E/C) [TW-yr/GtC]	Sequestra rate [GtC
Gas	1200	570	2.1	1.9 - 1.6	5 - 6
Oil	1200	750	1.6	1.4 - 1.2	7 - 8
Coal	4800	3690	1.3	1.2 - 1.0	9 - 10

Nuclear Fission/Fusion



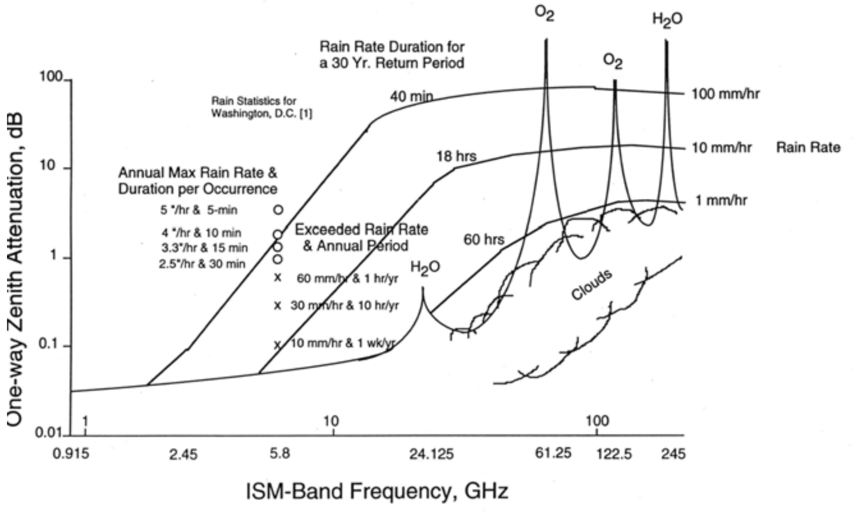
Solar Power Satellite

- 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

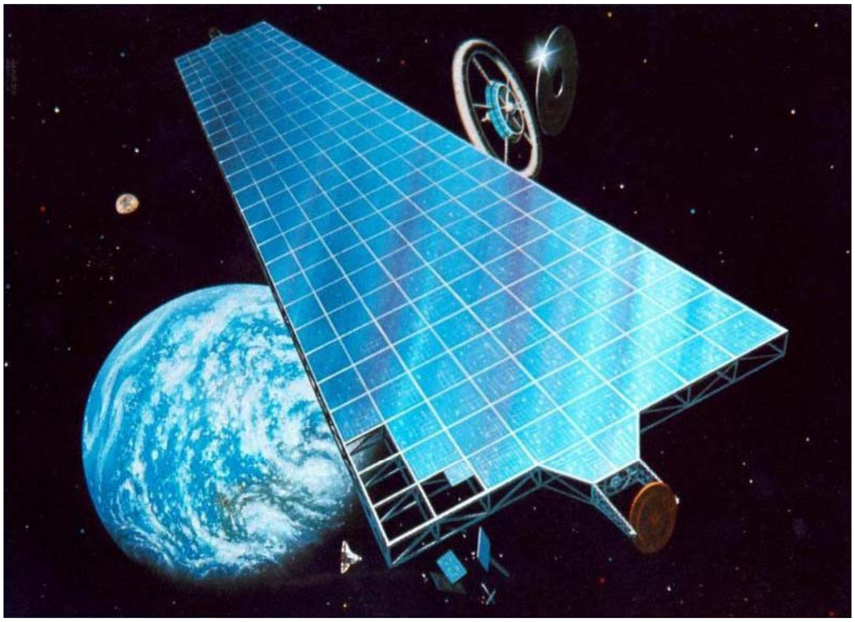
SPS Foundations

- Wireless Power Transmission
  - Raytheon experiments
  - NASA/Raytheon experiments
- Solar Power Satellite — Dr.Peter Glaser, 1968
- DOE/NASA definition study, 1977-1980

Microwave atmospheric absorbtion

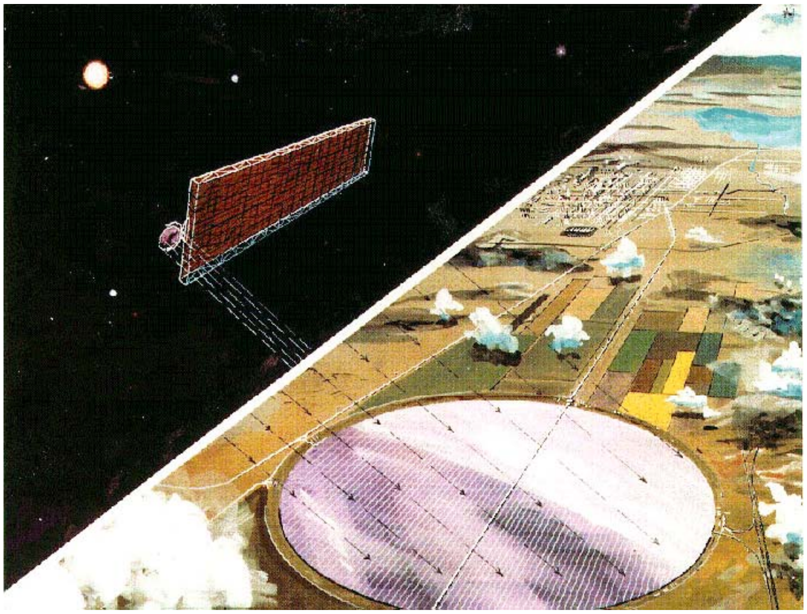


1] Propagation Effects Handbook for Satellite Systems Design, Louis J. Ippolito, NASA Ref. Publication 1082(04), Feb. 1989.



Solar Power Satellite Concept

Reference System concept



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

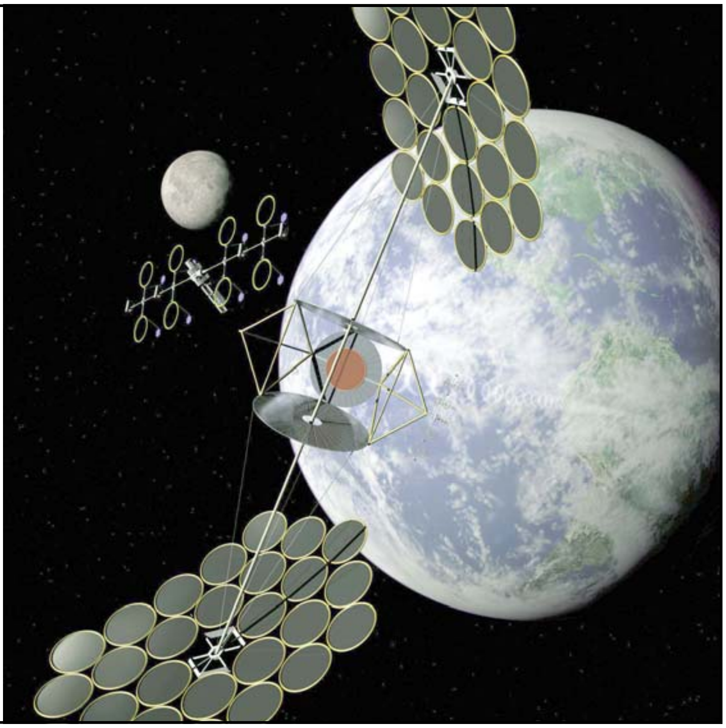
- Study of terrestrial wireless power transmission for remote village in Alaska
- 1995 NASA Fresh Look study evaluated progress on space based solar power
  - Emphasis on economic evaluation
  - Featured 5.8 GHz wireless power transmission
- SPS 2000
  - 10 MW transmitted
  - 1100 km circular equatorial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

Rectenna

5.8 GHz GEO transmission efficiency

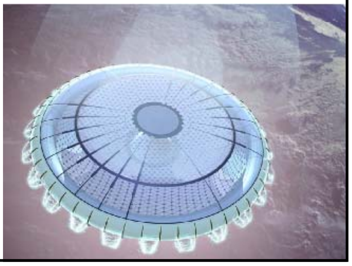
Nadir Beaming Distance (km) = 35,786
Transmitted Diameter (m) = 500
dc Power into transmitter (MW) = 2847
Grating Lobe Margin (%) = 3.8
Element Spacing (λ) = 0.871
Element Area (cm?) = 23.402
Elements/m? = 427
Mass Density (kg/m?) = 13.7
Element Mass (g) = 32.08
Total # Elements = 83,841,253
Total Transmitter 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 Angle @ Scan from Broadside (deg.) =	0.00	43.71
Scan slant range (km) =	35,786	37,322.7
RF Circuit Efficiency:	Efficiency	Efficiency
GaN RF Power Amp. PAE	0.900	
RF Filter Insertion Loss	0.8913	
RF Circuit Efficiency =	80.21%	
RF Power Into Antenna (MW) =	2283.65	

Scan Angle (deg.) =	0	6
Transmitter Efficiency:	Efficiencies:	Efficiencies:
Subarray Random Electronic Failures	0.960	
Element Failures from Meteorite Hits	1.000	
Amplitude Errors	0.996	
Phase Errors	0.978	
Phase Quantization	0.997	
Quantisized Taper Efficiency	0.989	
Aperture Efficiency	0.950	
Transmitter Scan Loss	1.000	0.995
Mismatch Loss	1.000	1.000
Antenna Efficiency =	87.50%	87.02%
RF Power Transmitted (MW) =	1,998.20	1,987.25
RF Peak Power Density on Transmitter (kW/m?) =	23.767	
Beam Coupling Efficiency:		
Propagation Loss	0.979	0.954
Beam Coupling Efficiency	0.921	
Polarization Efficiency	1.000	1.000
Beaming Distance (km) =	35,786	37,323
RF Power Incident on Rectenna (MW) =	1799.9	1745.8
RF Peak Power Density on Rectenna (mW/cm?) =	10.096	9.23
Rectenna Edge Power Density (mW/cm?) =	0.69	0.68
Rectenna Efficiency:		
Rectenna Array VSWR =	1	1
Rectenna Random Failures	0.990	
RF Filter Insertion Loss	0.891	
Rectenna Scan Loss	1.000	1.000
Mismatch Loss	1.000	1.000
Rectenna Efficiency	0.820	
Rectenna Efficiency =	72.35%	72.35%
DC Power From Rectenna (MW) =	1302.2	1263.1
DC Power Into Utility Grid (MW) =	1,237	1200
System DC-DC Efficiency =	43.45%	42.15%

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

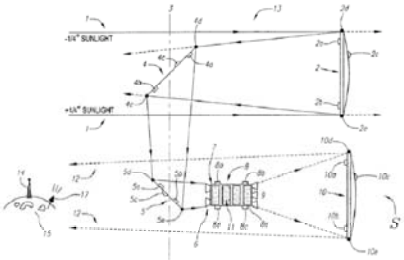


FIG. 1A

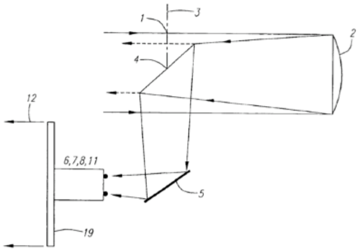


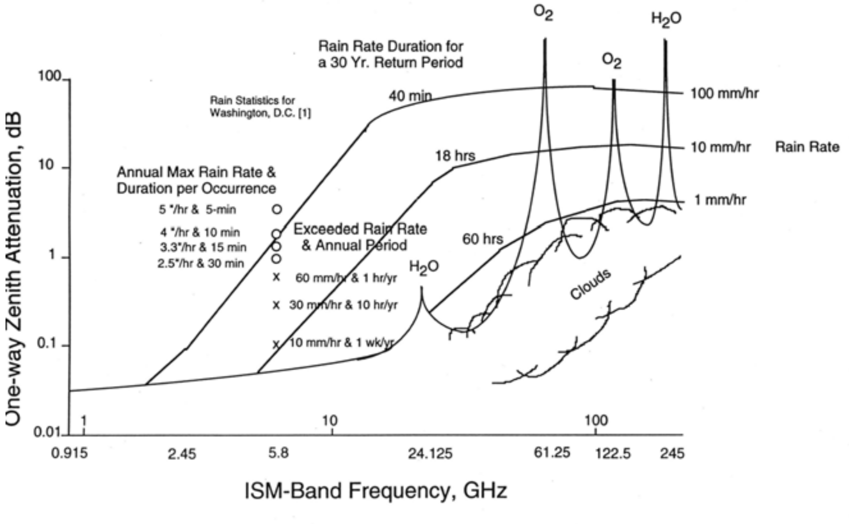
FIG. 1E

Solaren Patent figures for reflected transmission (left) and phased array (right) showing formation flying solar power satellite elements

Wireless Power Transmission for SBSP

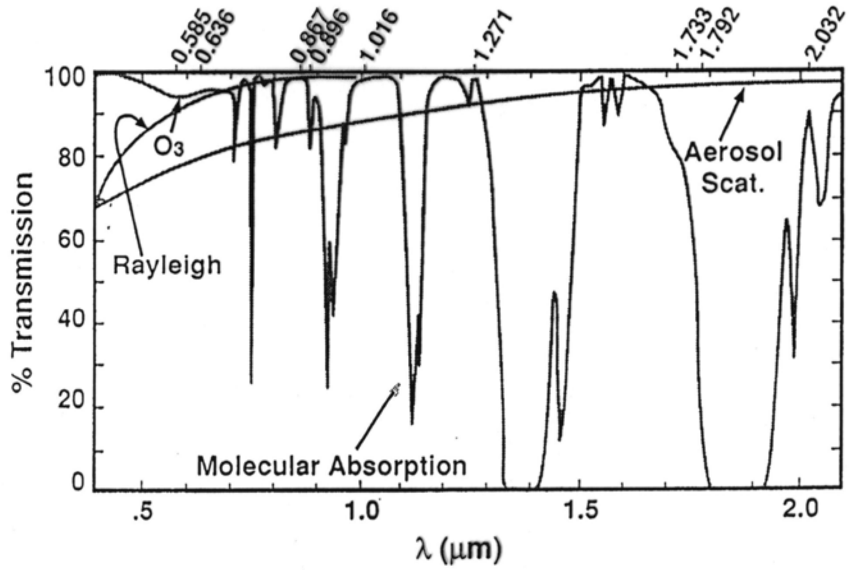
- Microwave
  - Wavelength <10GHz
    - Continuous power
    - Large aperture
    - Tapered beam
  - Single satellite system
    - High initial cost
  - System efficiency high
  - RF interference
  - RF safety issues
- Laser
  - Visible or near IR
    - Weather dependant
    - Smaller aperture
    - Uniform beam
  - Multiple satellites
    - Lower cost to “first beam”
  - System efficiency improving
  - No RF interference
  - Laser safety issues

Microwave atmospheric absorbtion



1] Propagation Effects Handbook for Satellite Systems Design, Louis J. Ippolito, NASA Ref. Publication 1082(04), Feb. 1989.

Laser atmospheric absorbtion



Beam Coupling Efficiency

Microwave Aperture Coupling

$\eta_b \sim 1- \exp(-\tau^2)$

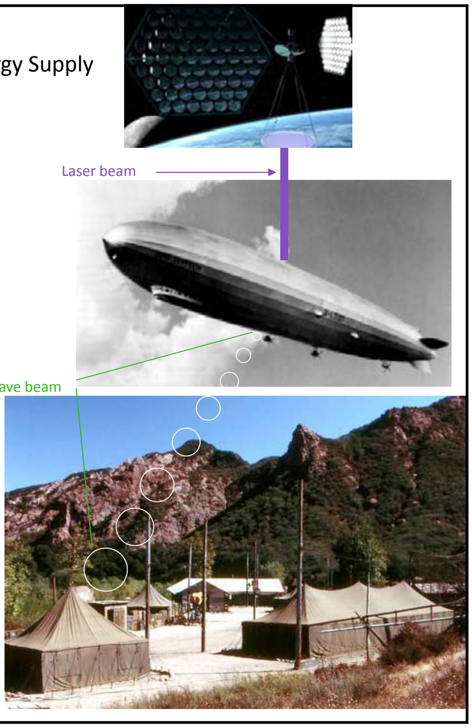
$\tau = \pi D_t D_r/(4\lambda R)$

Laser Diffraction Limit

r(receiver) = 0.61 d λ/r(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

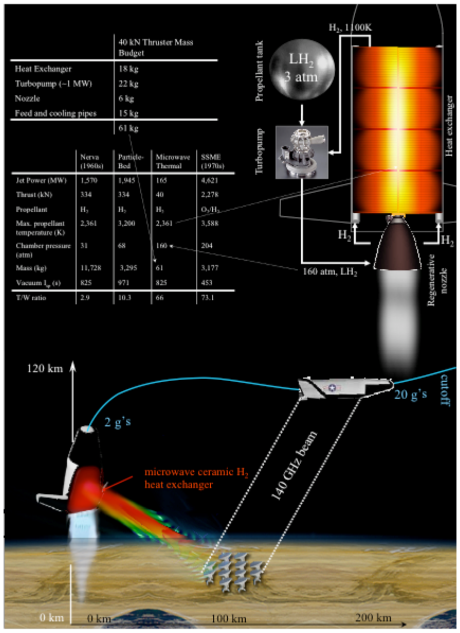
- Point-to-point to remote sites
  - Strait of Belle Isle in Newfoundland, Canada
  - Grand-Bassin on La Réunion
- Long duration aircraft
- Earth-to-orbit small satellite launch
- Remote charging of electric vehicles

Microwave Thermal Propulsion*

Beam heats ceramic heat exchanger

H_2 in chamber heated to >2300 K and >160 atm

Beam tracks rocket through ascent



	40 kN Thruster Mass Budget
Heat Exchanger	18 kg
Turbopump (~1 MW)	22 kg
Nozzle	6 kg
Feed and cooling pipes	15 kg
	61 kg

	Nerva (1960s)	Particle-Bed	Microwave Thermal	SSME (1970s)
Jet Power (MW)	1,570	1,945	165	4,621
Thrust (kN)	334	334	40	2,278
Propellant	H_2	H_2	H_2	O_2/H_2
Max. propellant temperature (K)	2,361	3,200	2,361	3,588
Chamber pressure (atm)	31	68	160	204
Mass (kg)	11,728	3,295	61	3,177
Vacuum I_{sp} (s)	825	971	825	453
T/W ratio	2.9	10.3	66	73.1

* 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

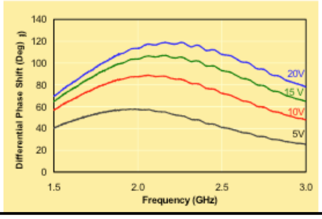
- Political
  - Spectrum Allocation
  - Perception
    - Militarization of space
    - “Fear of frying”
- Technology
  - Efficiency
  - Frequency
  - Control
  - Materials
- Beam safety
  - Energy density
  - Ionosphere interaction
- Demonstration
  - Space
  - Terrestrial

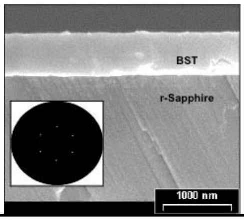
Current Component Efficiencies

- 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

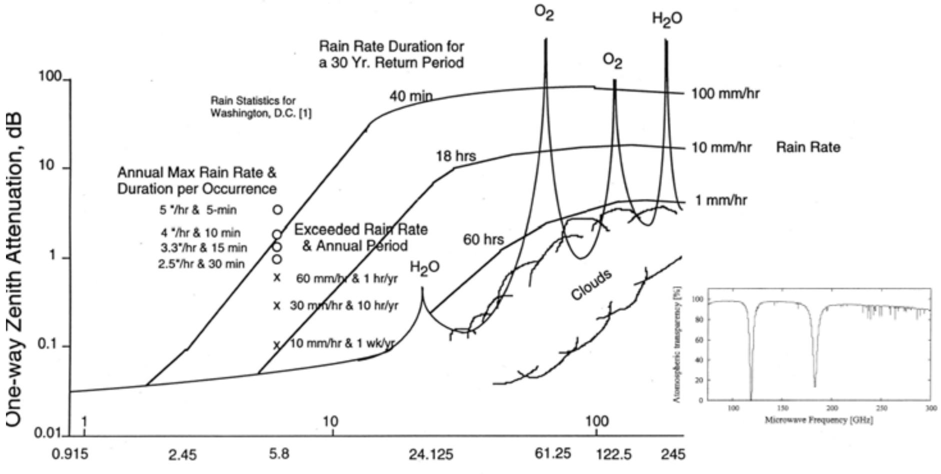
Electronic Component Improvement

- 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 shifte
- Solid state and fiber optic laser





Microwave atmospheric absorbtion



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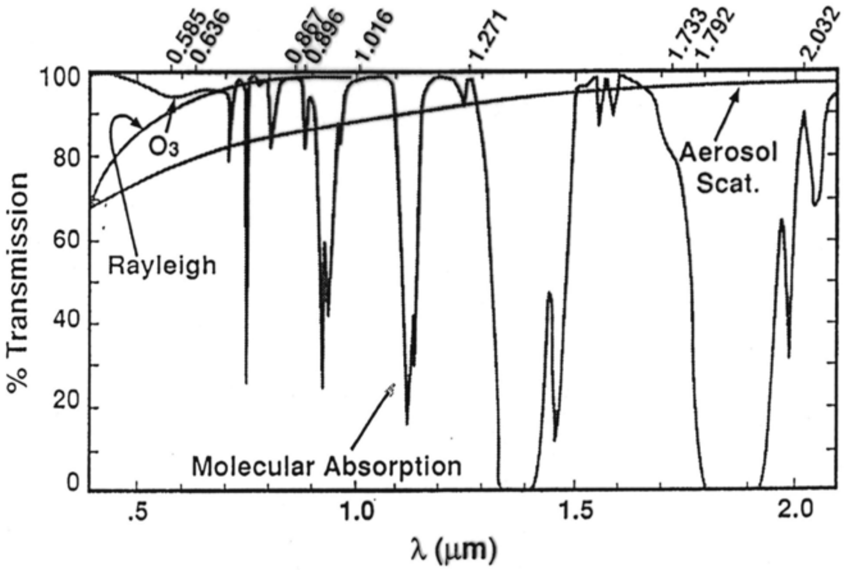
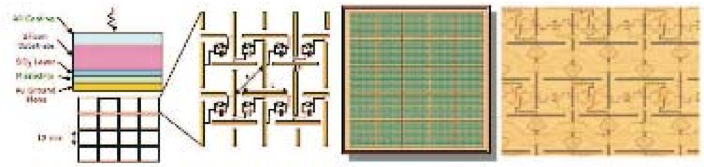
Laser atmospheric absorbtion



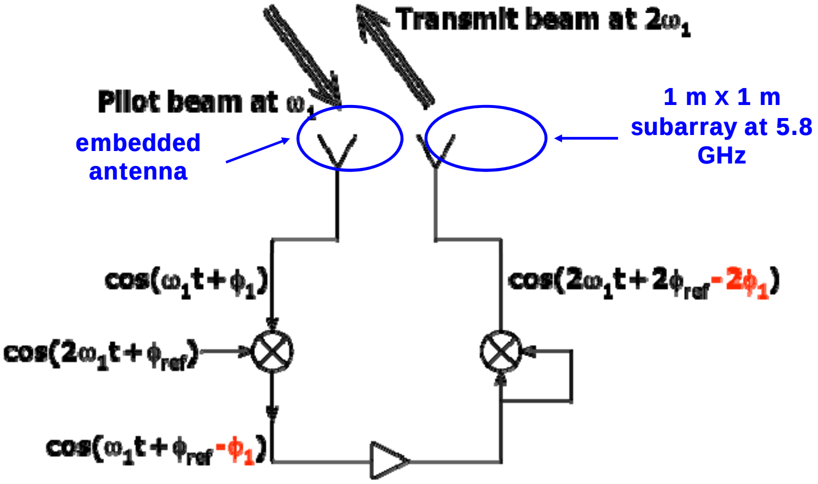
High Frequency Electric Transmission

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



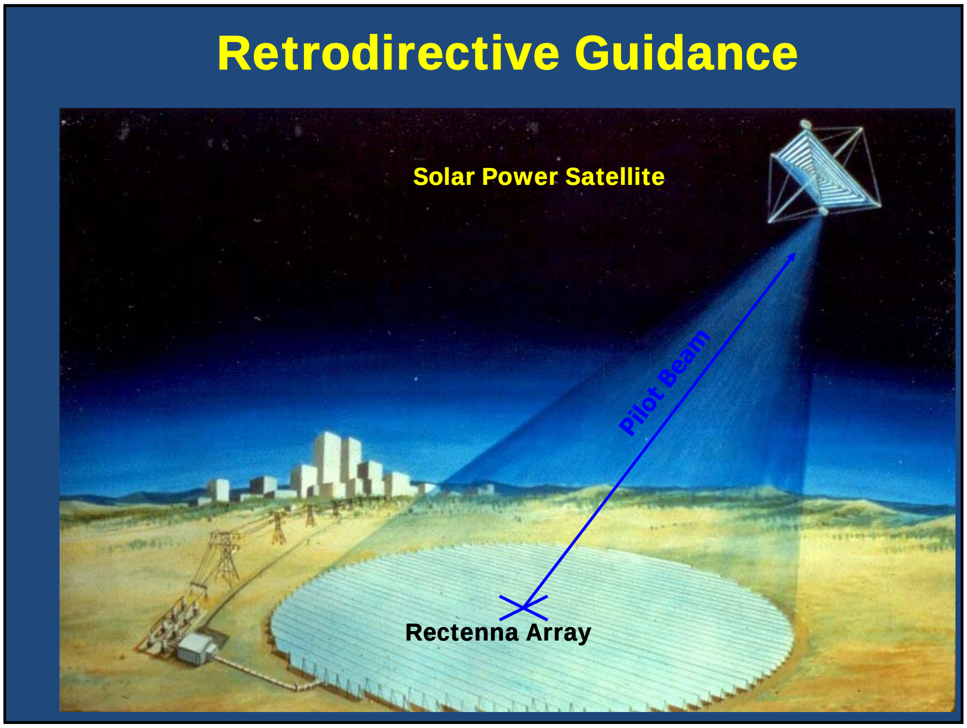
Beam Control and Steering

2^{nd} Harmonic Retrodirective Array



Retrodirective System

- 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

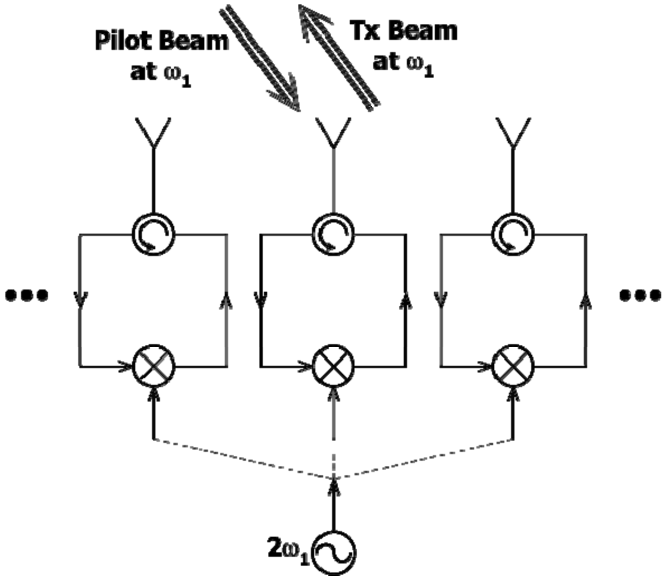


Retrodirective Guidance

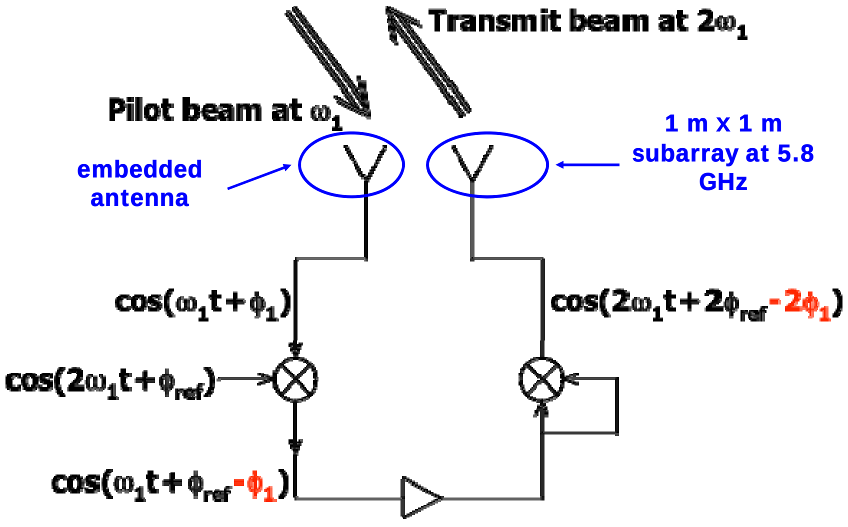
Retrodirective Guidance

- 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

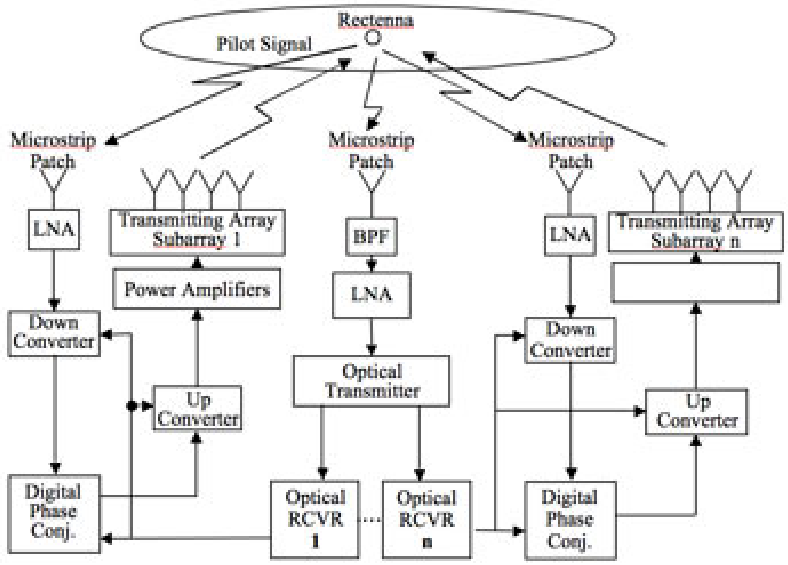
Classic RF retrodirective array



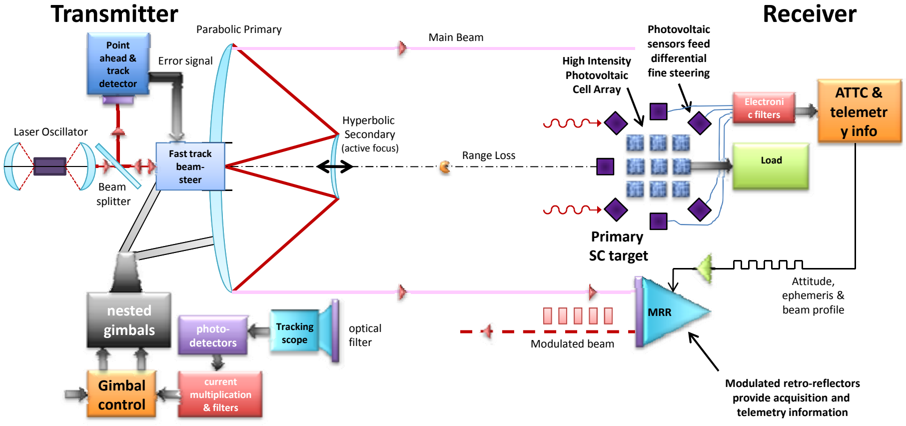
2nd Harmonic Retrodirective Array



Software Retrodirective System



Optical Retro-Directive Beam Control Architecture

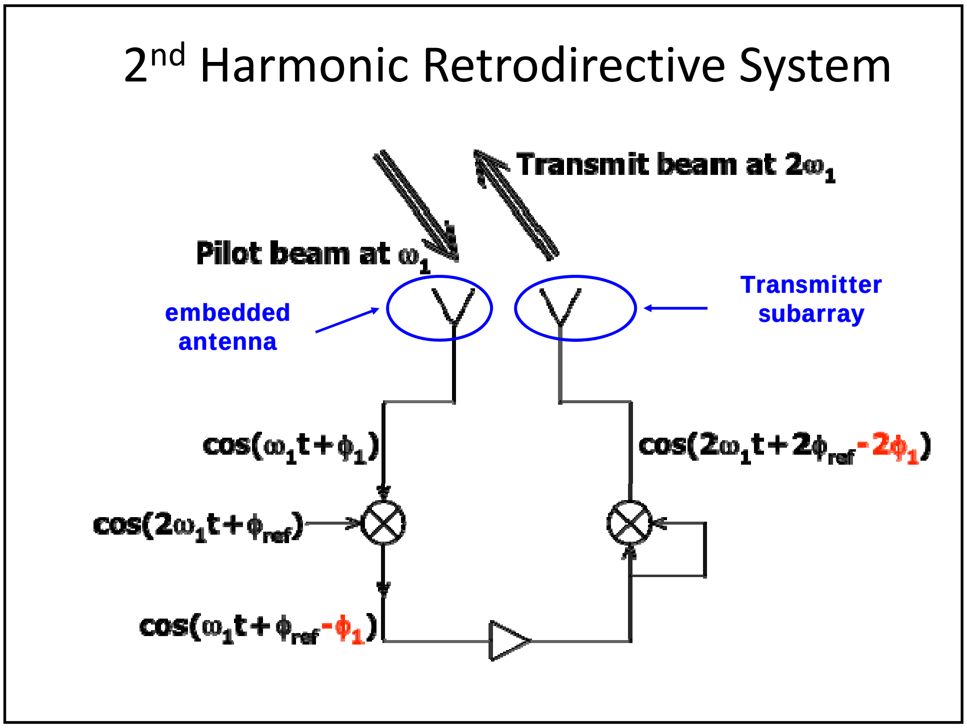


Faster Electronics

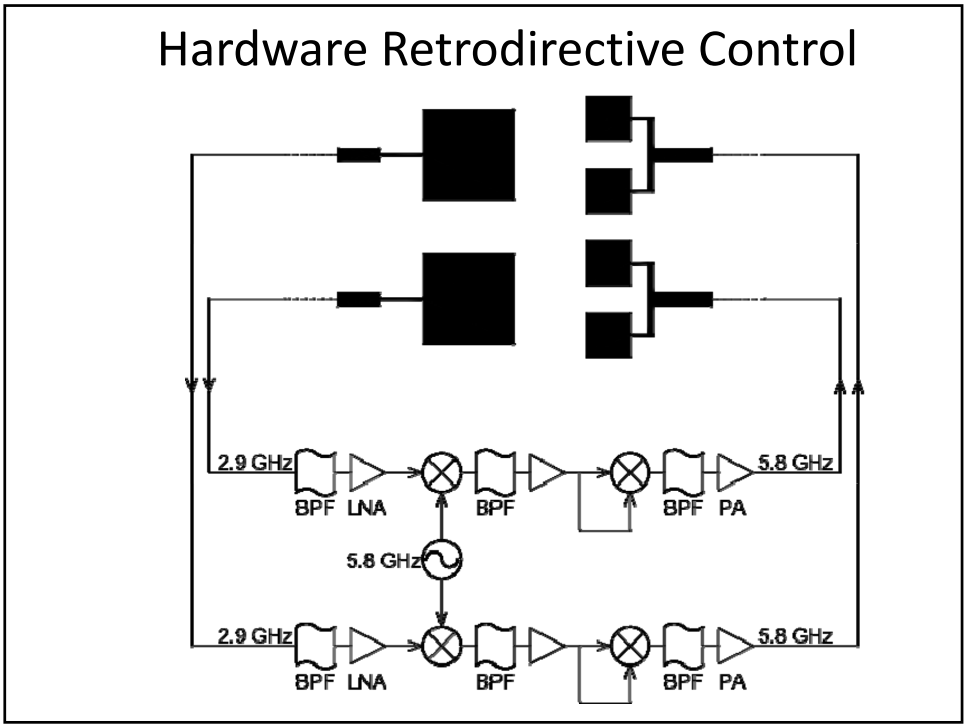
- Software controlled retrodirective beam
  - Improved digital signal processor to enable high frequency conjugate phase angle calculation
  - High speed broad bandwidth ADC-DAC (12.5 GS/sec)

Materials

- Influences nearly all aspects of WPT
- Enables technology

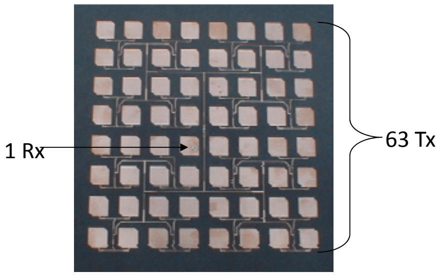


2nd Harmonic Retrodirective System

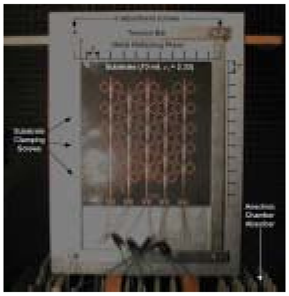


Hardware Retrodirective Control

5.8 GHz Hardware

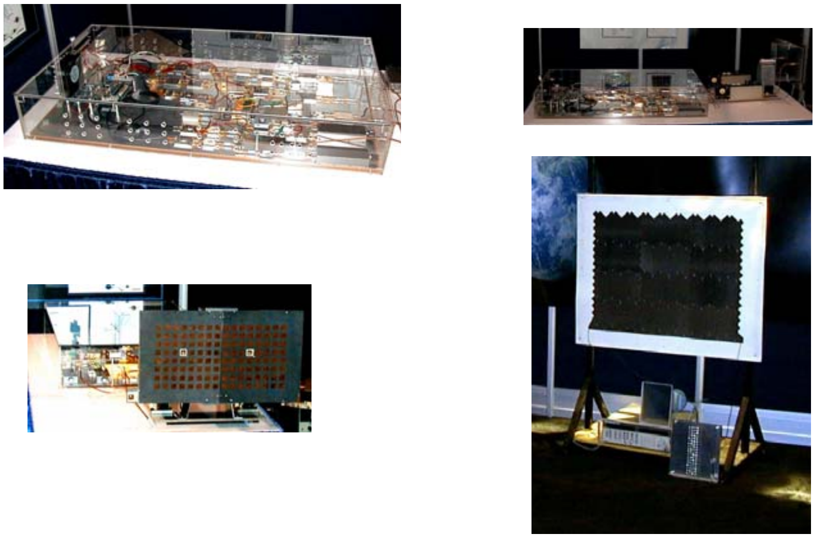


Solid state transmitter panel



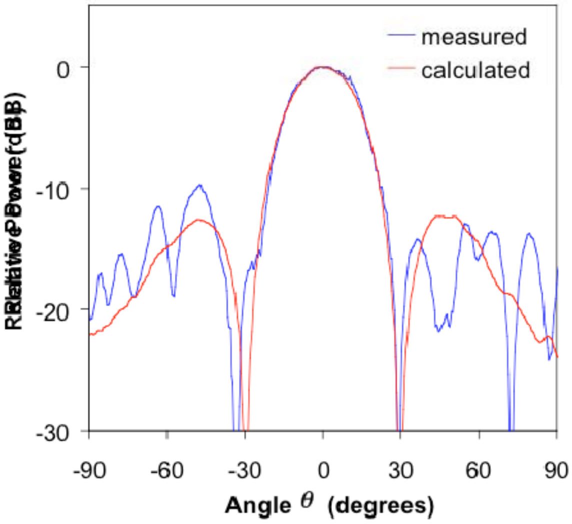
Circular polarized rectenna

Hardware at World Space Congress



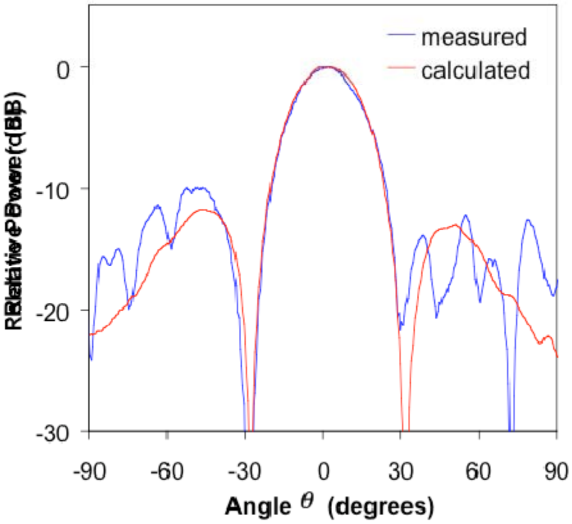
Measurement

broadside pattern



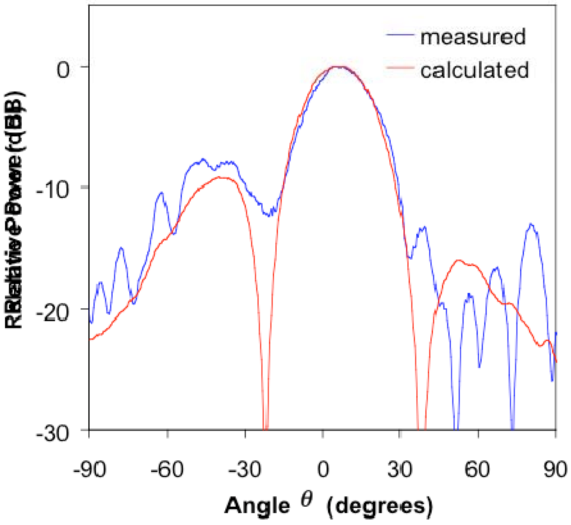
Measurement

pattern steered to 2º



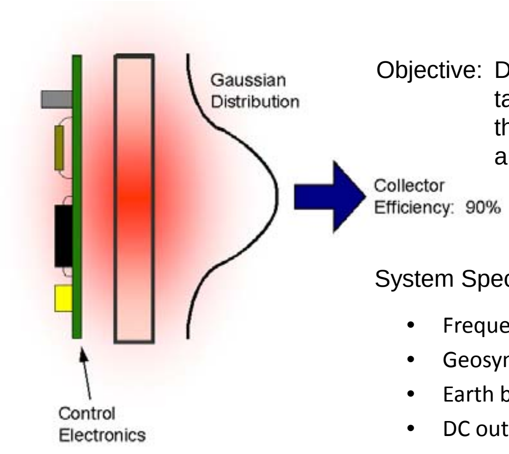
Measurement

pattern steered to 7º



Antenna thermal management

Definition of Problem and Specifications



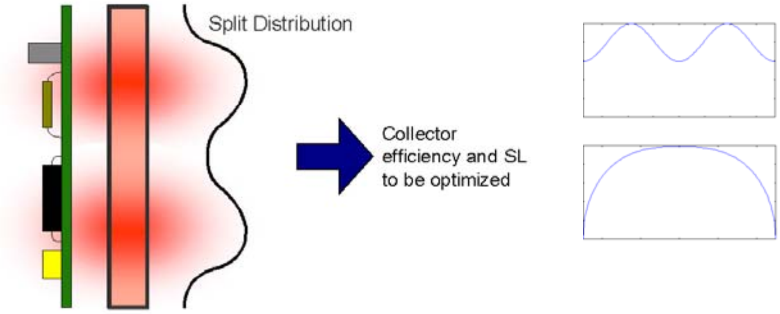
Objective: Design and optimize transmitter taper for efficiency while reducing thermal constraints at center of antenna

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

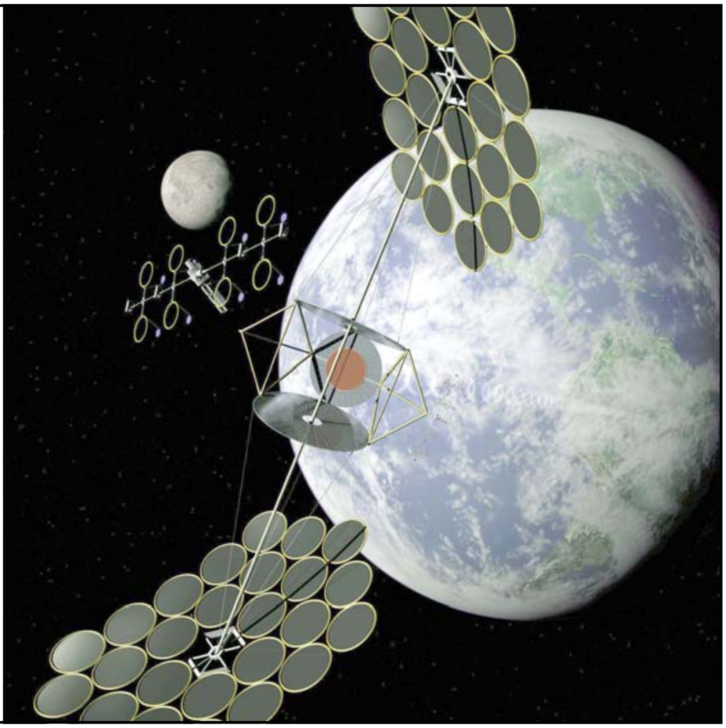
Proposed Solution



- 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

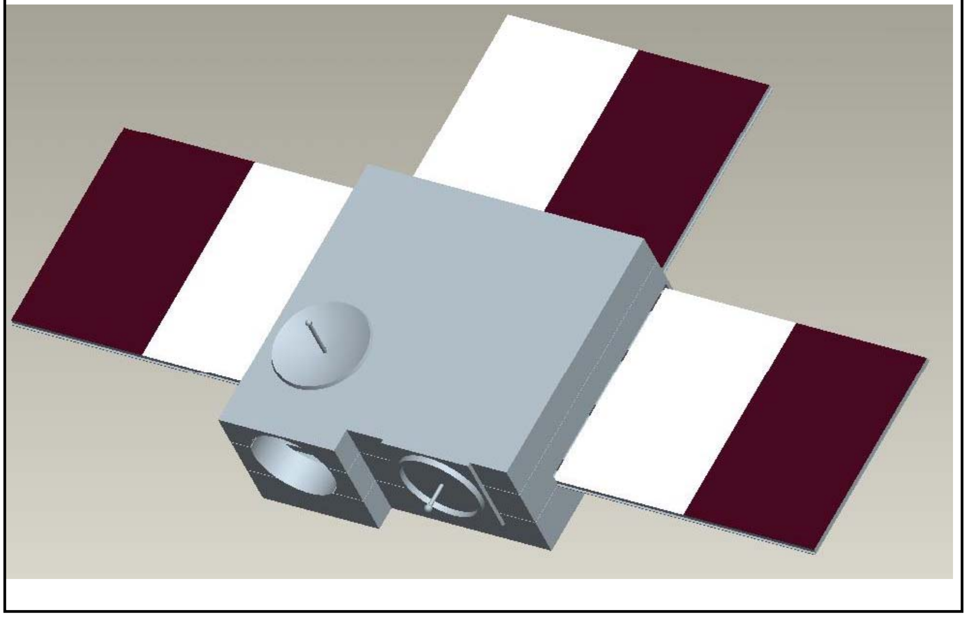
Hardware Design Goals

- 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

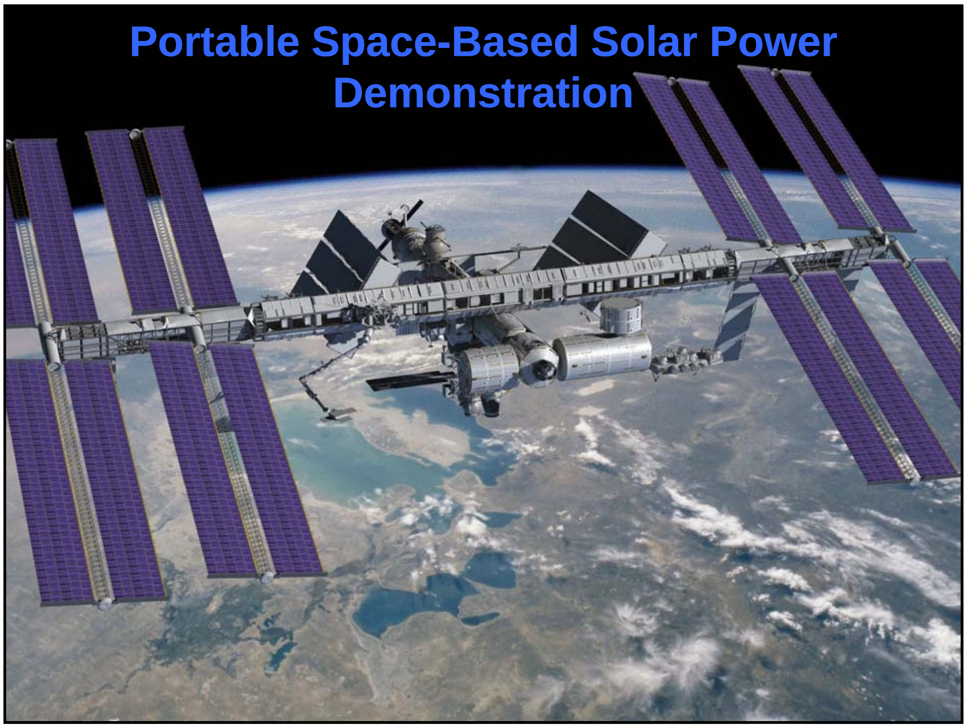
Experimental Package



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

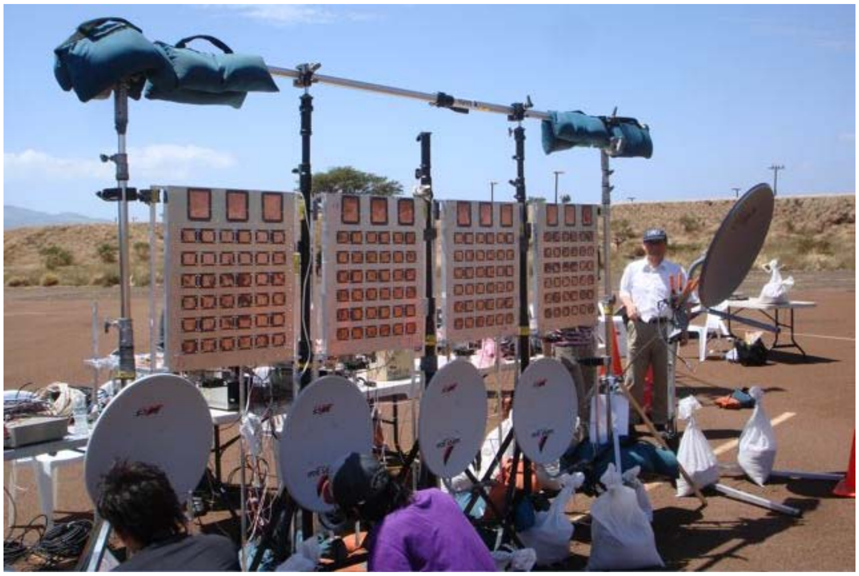


Microwave Beaming Demonstration

End-to-end retrodirective microwave beaming system demonstration

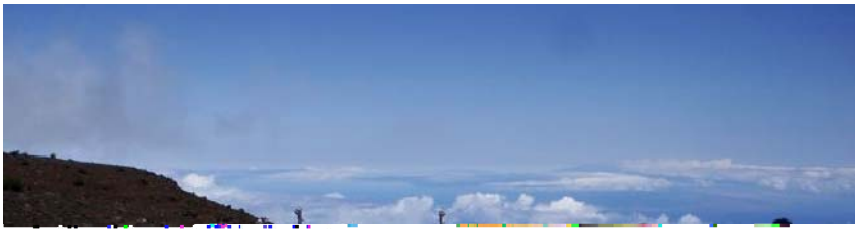
Collaborative project with Managed Energy Technologies and Kobe University

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

Statement	strongly agree	Partly agree	either way	partly disagree	strongly disagree
This class was the first time that I had ever heard of the concept of space solar power.	9	1	1	0	5
As a student, the end-of-term Microwave Power Transfer Symposium is a valuable experience and worth the time to attend.	7	7	1	0	0
The website format of the final report is preferable to a conventional final written report.	7	6	3	0	0
I would have preferred an individual project to the group project.	0	2	4	5	5
I do not like the competitive aspect of the group project.	0	3	6	5	2
The Space Solar Power group project made this class more work than the average graduate engineering course.	1	8	4	2	1
As a result of the Space Solar Power project, I have more interest and appreciation of RF engineering.	4	9	3	0	0
As a result of the Space Solar Power project, I have more interest and appreciation of solar cells and/or microelectronics.	1	8	5	2	0
As a result of the Space Solar Power project, I have more interest and appreciation of antennas and/or electromagnetic waves.	5	6	5	0	0
As a result of the Space Solar Power project, I have more interest and appreciation of system engineering concepts.	5	7	3	1	0
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.	1	4	3	4	4
As a result of this class and project, I plan to study space solar power more in the future.	0	6	5	3	2