Space Solar Power Initiative (SSPI) – Results & Paths Forward

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Outline

- The Initial Concept That Started SSPI
- SSPI Goals And Objectives
- Technical Approach
- Prototyping and Test Results
- System Considerations
- Lessons Learned
- Space Solar Power Project (SSPP)

Insight by Three Caltech Professors – Reduce Mass of Space Segment by Introducing New Technology

- Profs. Harry Atwater, Ali Hajimiri and Sergio Pelligrino collaborated on an idea to make an ultra-light space solar power satellite
  - Employ "sandwich" module architecture[1]
  - Reduce mass of PV material by using ultra-light concentrators and ELO fabricated GaAs PV
  - Reduce mass of RF assembly by using a single CMOS IC to convert DC to RF power, adjust RF phase, and drive local antennas
  - Reduce structure of satellite by making a membrane-like surface for the PV/RF which can be folded and rolled for compact stowage
- These four ideas formed the basis of SSPI

SSPI is a Collaboration Across 3 Different Departments

Atwater Group

Applied Physics & Material Science

Prof. Harry Atwater

Dr. Michael Kelzenberg

Dr. Emily Warmann

Dr. Pilar Espinet Gonzalez

Dr. Tatiana Vinogradova[1]

CHIC Group

Electrical Engineering

Prof. Ali Hajimiri

Dr. Florian Bohn

Dr. M. Hashemi

Mr. Austin Fikes

Pellegrino Group

Aerospace Engineering

Prof. Sergio Pellegrino

Dr. Terry Gdoutos

Dr. Armanj Hasanyan

Dr. Nina Vaidya,

Mr. Michael Marshall

Mr. Fabien Royer

Mr. Alan Truong

Mr. Christophe Leclerc

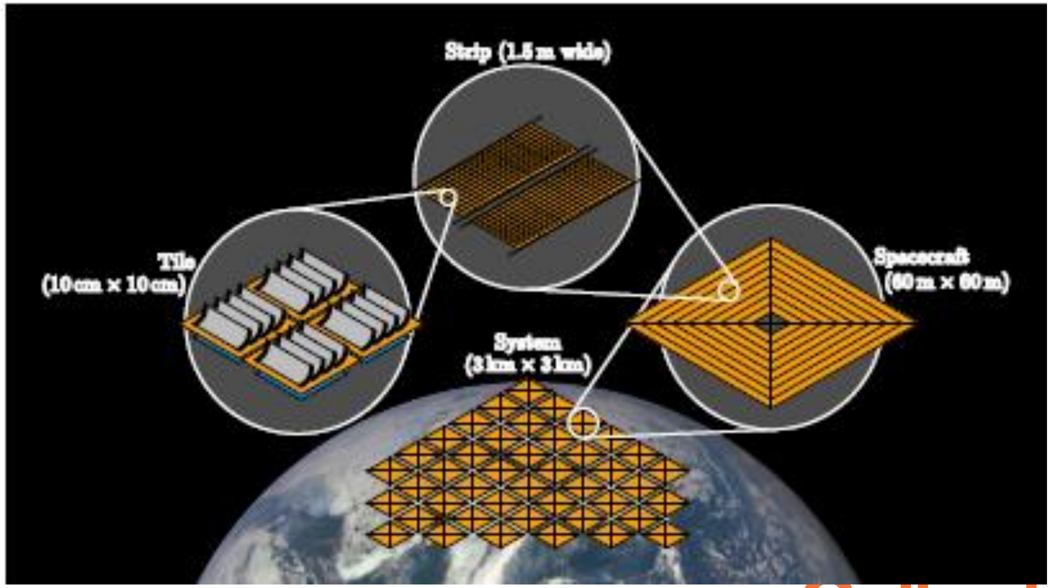
Plus about 12 part time contributors

1 - Visitor Status

Caltech/Northrop Grumman Space Solar Power Initiative (SSPI)

2015 - 2017

- In 2015, Northrop Grumman undertook three year funding for the project [2]
  - Began maturation of concepts developed with initial gift
- 2015 – research on PV approach, CMOS IC architecture, and structural trades
- 2016 – initial designs and lab models
- 2017 – Two prototypes fabricated and tested
- Lessons learned help get Space Solar Power Project moving



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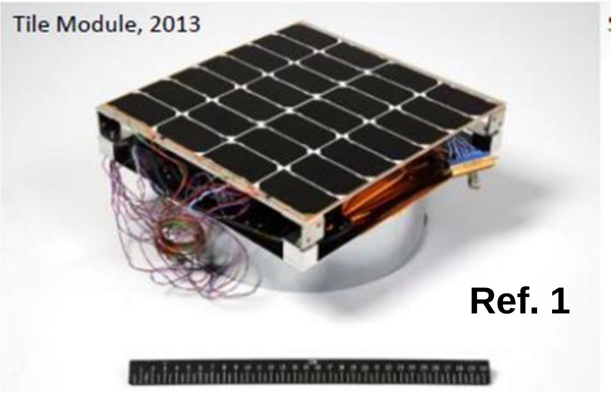
The Tile is a Fundamental Unit With All The Functionality Required to Convert Solar Energy to RF Energy & Radiate It

- Architecture similar to P. Jaffe's [1] sandwich module
- Caltech tile concept circa 2015 – 2017
  - Use of concentrators to reduce mass of PV
  - CMOS ICs for power conversion, phasing & radiating
  - Metallize Kapton layer for patch antennas
- No lateral transport of DC power
  - Eliminate cabling and structure



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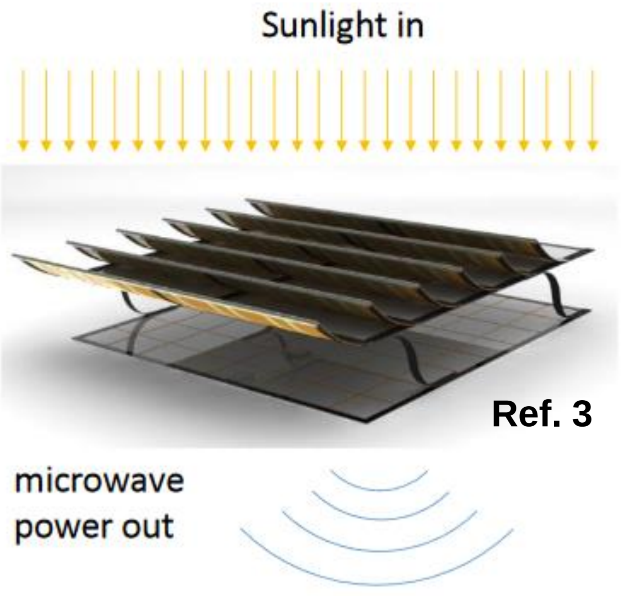

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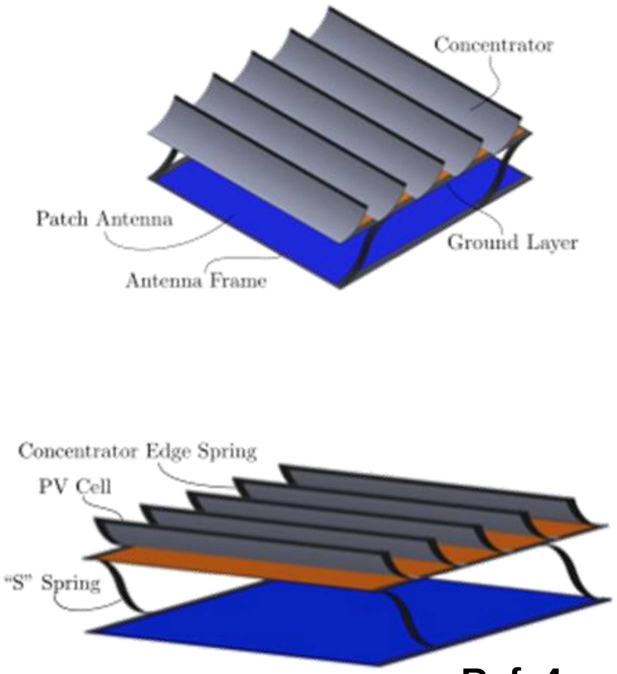

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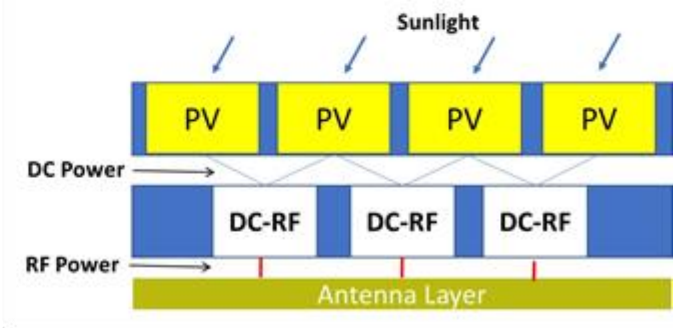

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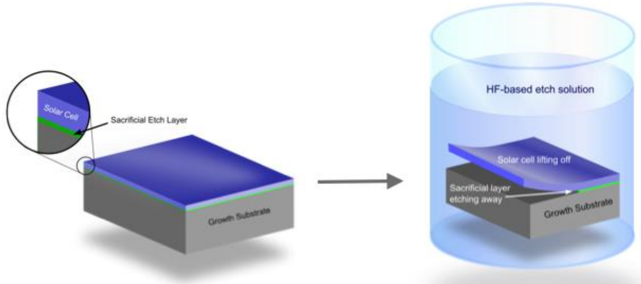
Three Major Technical Thrusts

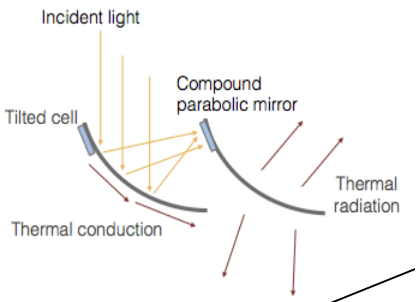
Flexible, high efficiency PV

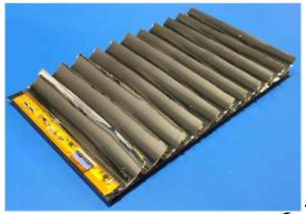


Multi-junction GaAs cells fab'ed with ELO technology [4]

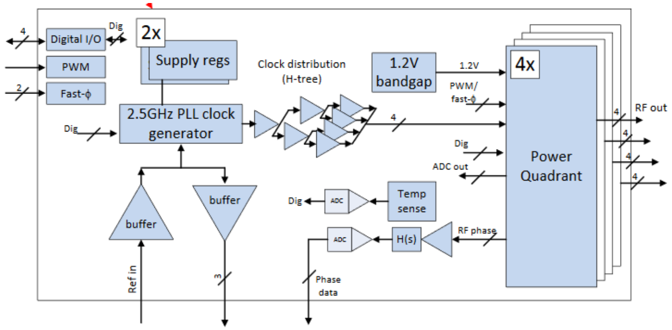
Ultralight concentrators

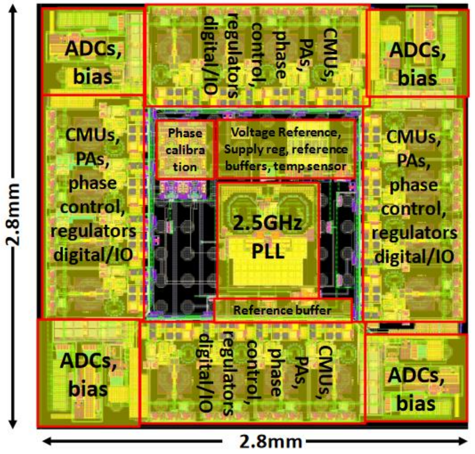
Efficiency ~ 27 – 30%





CMOS RF power conversion and phase control

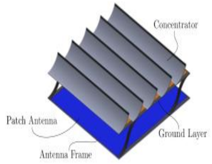


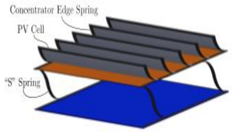


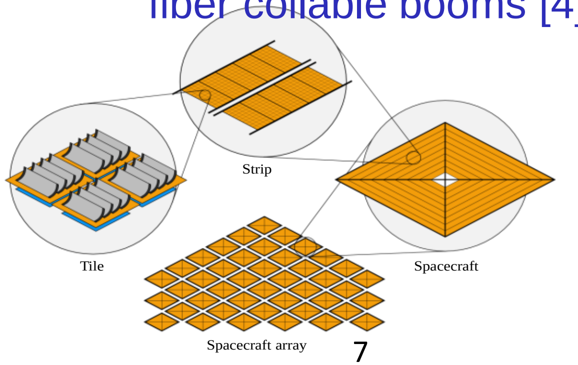
Projected ~50% DC/RF conversion efficiency
Tile-to-tile timing jitter << 10° phase error [4]

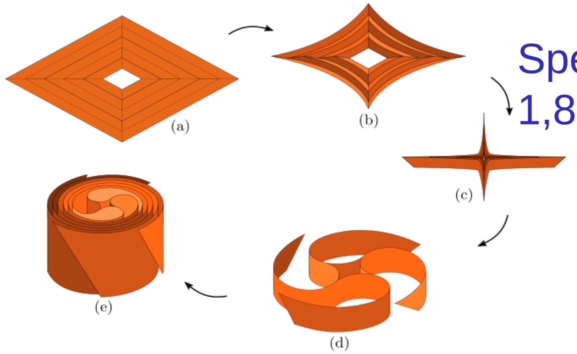
Structures & Mechanisms

Membrane-like structure that can be folded and rolled for stowage, and deployed using carbon fiber coilable booms [4]









Specific RF power > 1,800 W/kg

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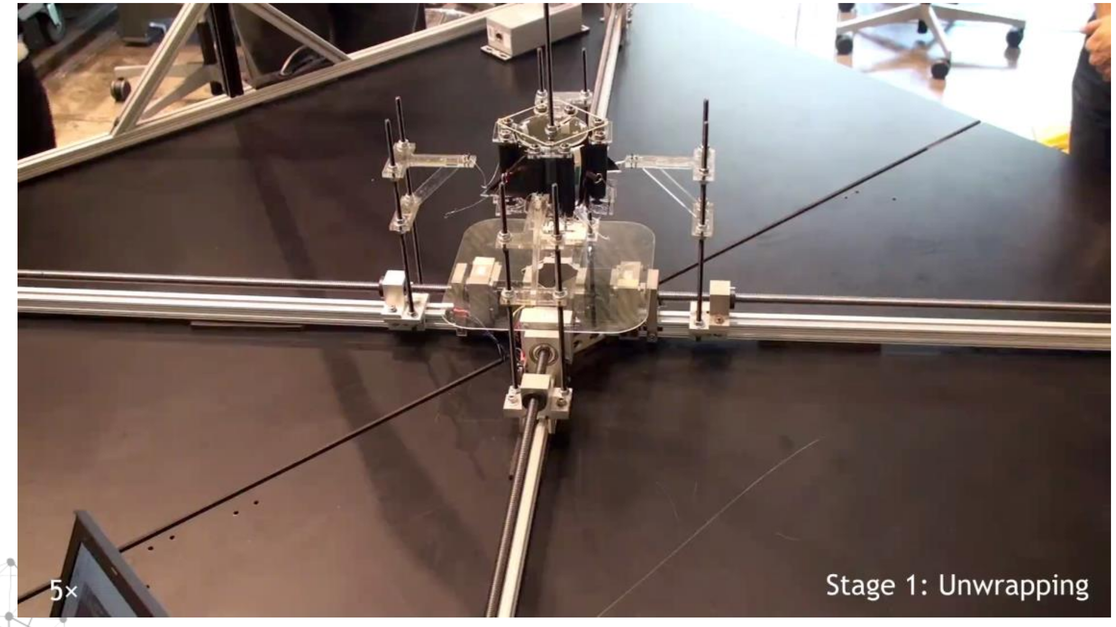
Prototype Tile and Deployment Model Demonstrated in 2017

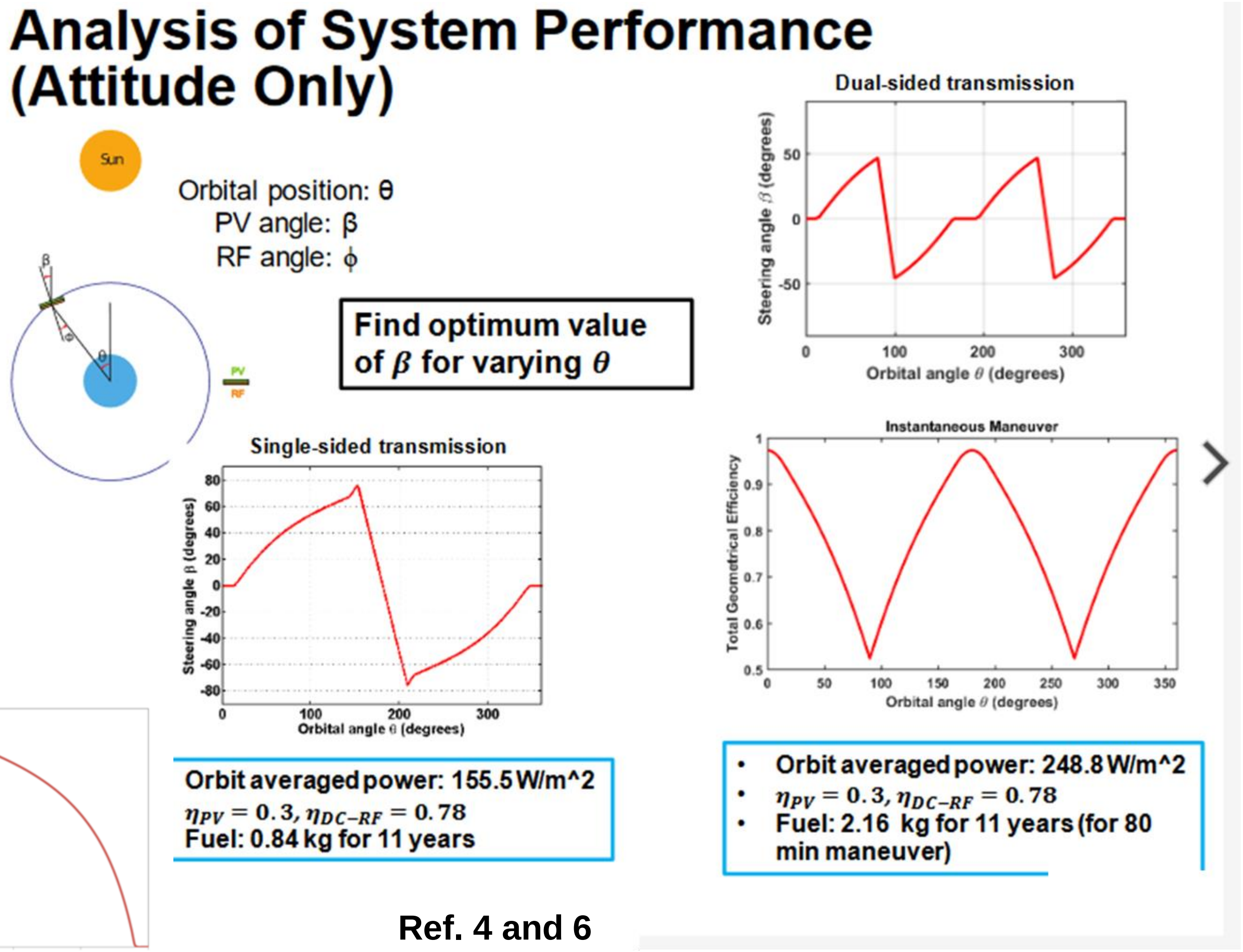
- Prototype fabricated using tailored GaAs PV material
- Concentrators made of carbon fiber shells to maintain shape
- CMOS RF IC fabricated at TMSC
- Area mismatch between PV and RF IC



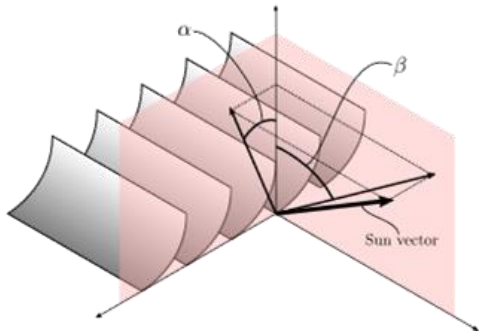
- Surrogate material used to demonstrate folding and rolling concept
- Lab scale demo packed ~ 1m2 membrane into cylinder ~ 10 cm diameter cylinder, ~ 12 cm high
- Successful demonstration

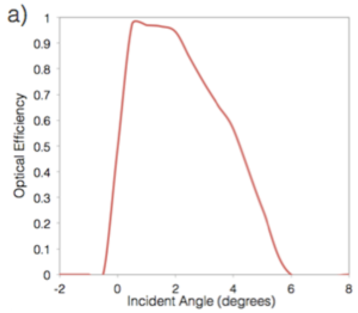
SSPI Satellite Geometry Limits Ability to Provide Energy to Ground

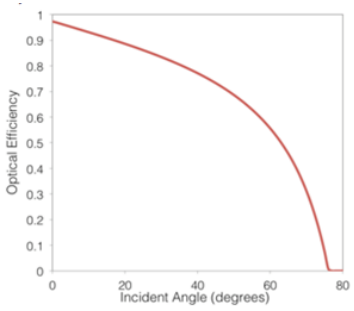
- Flat plate geometry coupled with sun pointing constraint for PV concentrator limits ability to deliver energy to earth
- A single sided system delivers about 62% of the energy that a dual sided system can deliver (total duty cycle < 45%) [5]
- Need to modify SSPI concept to permit either dual sided RF transmission or dual sided PV energy collection



Ref. 4 and 6







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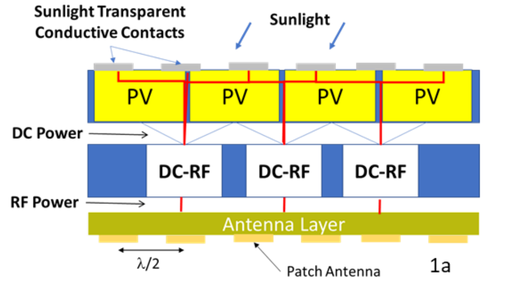
Lessons Learned Informed Space Solar Power Project (SSPP)

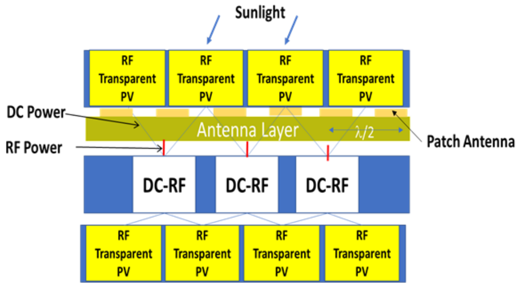
- Concentrators difficult to fabricate using ultralight materials
  - Very hard to obtain correct shape – large mass penalty incurred going to carbon fiber shells
  - Concentrator to concentrator alignment drives assembly time
- Substrate materials require higher thickness than initially thought
- Ability to transmit RF out of both faces (or collect sunlight on both faces) necessary to achieve reasonable levelized cost of electricity
  - Concentrators would require new solution that is RF transparent and provides the thermal control required for the PV
- SSPP took up where SSPI left off using the lessons learned

SSPP Building off the Successes and Lessons Learned

- Two sided capability is a “must have”!
- PV
  - Move away from concentrators
  - Looking for RF transparent PV solutions or conductive layers that are transparent in the visible band (e.g. Indium Tin Oxide)
  - Researching perovskites and other emerging PV technologies
- RF
  - Refining CMOS IC design
  - Researching antenna options & timing and reference distribution
  - Supporting PV group in searching for RF compatible technologies
- Structures and Mechanism
  - Continued maturation of structure and deployment mechanism
- System Analysis
  - Tools for evaluating impact of different technology paths[7]
  - Alternative orbits [8]
- On-orbit demonstration planning and execution



1a



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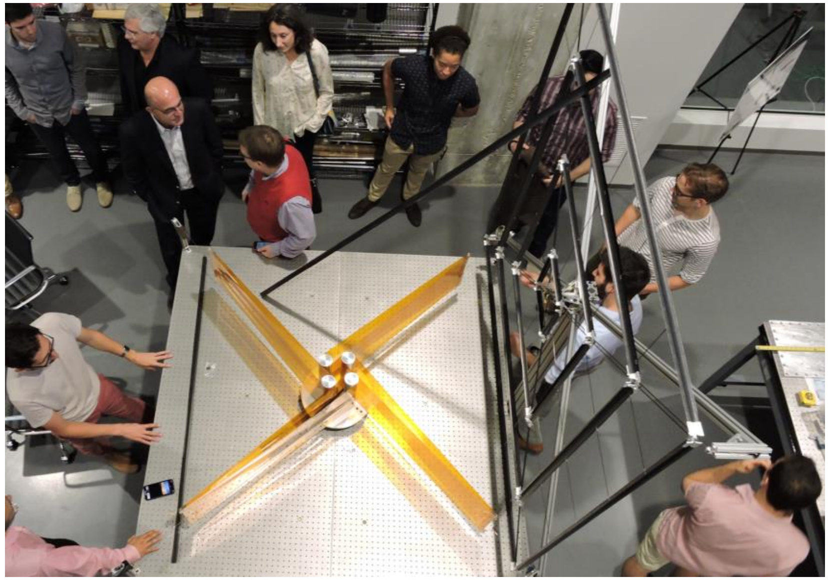

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References

1. P. Jaffe, “Sunlight To Microwave Power Transmission Module Prototype For Space Solar Power”, Doctoral Thesis, University of Maryland College Park, 2013
2. https://www.caltech.edu/about/news/space-based-solar-power-project-funded-46644
3. E. Gdoutos, C. Leclerc, F. Royer, et. al., A Lightweight Tile Structure Integrating Photovoltaic Conversion and RF Power Transfer for Space Solar Power Applications, AIAA SciTech Conference, Kissimmee, FL, January 2018
4. “A Lightweight Space-based Solar Power Satellite”, in preparation by SSPP team
5. M. Arya, N. Lee, S. Pellegrino, Ultralight Structures for Space Solar Power Satellites, AIAA SciTech Conference, San Diego, CA, January 2016
6. M. A. Marshall, A. Goel, and S. Pellegrino, “Power-optimal guidance for planar space solar power satellites,” 2019, in preparation.
7. R. G. Madonna, Use of an Iterative Research and Development – System Engineering Approach for the Caltech Space Solar Power Project, IEEE WiSEE Conference, Huntsville, AL, December 2018
8. M. A. Marshall, R. G. Madonna, and S. Pellegrino, “Extension of power-optimal guidance for space solar power satellites to MEO and implications for space solar power systems”, 2019, in preparation