



# Challenges of Space Power Beaming: Forging production services from the technology development trade space

IEEE

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# Space Power Beaming & Ancillary Services

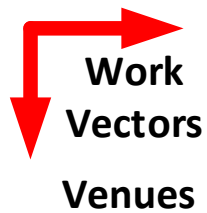
- (1) Key Considerations**
- (2) Key Variables**
- (3) The Challenge Matrix**
  - **The Problem Space**
    - **Ground & Space Technology Development**
  - **Solution Space**
    - **Demonstration**
    - **Deployment**
- (4) Visualization**
- (5) XISP-Inc Space-to-Space Power Beaming Example**
- (6) Mission Technology, Development, and Demonstration TD<sup>3</sup>**

# Space Solar Power Key Considerations

- Space Solar Power is an applied engineering problem and an economics problem.
- Applications have significant systems engineering and economic challenges in each venue that must be successfully addressed.
- Each venue has different fundamental figures of merit which define their value proposition.
- Operational capabilities are best realized by leveraging a combination of technology development “Push” and mission requirements “Pull”.
- Each increment of public and/or private investment should lead to an operational capability.
- Work Vectors: Technology Development → Demonstration → Deployment and Space-to-Space → Surface-to-Surface → Space-to-Alt Surface → Space-to-Earth

# Space Solar Power Key Variables

- Cost/Economics (initial cost to first power, LCOE, market viability, anchor customers),
- Frequency/Wavelength (microwave to eyesafe optical),
- Distance (near field, boundary regions, far field),
- Magnitude (i.e. power level supporting application)
- Duration (pulsed, scheduled, continuous),
- Availability (on demand, scheduled, prioritized, by exception),
- Security (misuse, interruption, destruction), and
- Performance (net transfer, end-to-end efficiency, piecewise efficiency, steering precision and accuracy, beam shaping, effective operational difference).



Space  
- to -  
Space

Surface  
- to -  
Surface

Space  
- to -  
Moon /  
Asteroid

Space  
- to -  
Earth

## Space Solar Power Problem Space

### Technology Development

#### Ground

- Cognitive SDR Transceiver
- Converged Electro/Optics
- W Band & Optical Apertures
- Piecewise Efficiency
- Reflectarray Rectenna
- Beam Forming
- Management Operations Control Applications (MOCA)

#### Space

- ISS Mounted Transceiver
- Deployable Rectenna
- 6U Flight Test Article
- Optimized Frequencies
- End-to-End Efficiency
- Scaling/Modularity (Gen, Trans, and Control)
- Multiplexing Services
- MOCA S/W & Data System

- Deployable Power Generation & Relay Towers
- Conformal Rectenna
- Deployable Rectenna
- Solar Concentrator/Reflector

- Powered Rover
- Powered Prospector
- Powered Miner
- Volatile/Metal Separation

- Disaggregatable Flight Systems Technology
- Scalable Transceiver
- Scalable/Printable Rectenna
- Management Operations Control Applications (MOCA)

- Mothership with deployable sensors/rovers
- Distributable Rectenna
- Lunar Resonant Orbits
- Beam Steering (Phased Array & Gimbals)

- Lunar Resource Model
- Asteroidal Resource Model
- Drive launch costs down to \$100/kg to LEO
- Atmospheric Transparency
- Beam Management -- Frequency/Control/Security
- MOCA Authentication, Authorization and Control System

- Modular Structure I/Fs (mechanical/robotic/control/thermal)
- Thermal Management
- Pointing Large Structures
- Electro-Magnetic/Optical Alignment
- Solar Dynamic Modules
- Non-Iridium Based Concentrated Photovoltaic

## Space Solar Power Solution Space

### Operational Capability/Applications

#### Technology Demonstration

- ISS Co-orbiting Crew Tended Free Flyer Demo
- Propulsion Augment Demo
- Space Based Propellant Depot Operations Demo
- Disaggregated Formation Flying Spacecraft Demo
- Plug in/Plug Out Tech Demo

- Power & Ancillary Services Beaming - Survive the Night
- Volatiles Mining Demo
- Propellant Depot Demo
- Metals Mining Demo

- Power & Ancillary Services Beaming Demo
- Lunar Assay & Mining Demo
- Asteroidal Assay & Water/Volatiles Mining Demo
- Asteroidal Optical Drilling, Volatiles Mining & Demo
- Metal Refining Demo
- Planetary Defense

- Power & Ancillary Services Beaming to UAVs & Others
- Power & Ancillary Services Beaming to Forward Bases
- Power & Ancillary Services Beaming to Terrestrial Grid

#### Technology Deployment

- Power & Ancillary Services Beaming Interface Kit(s)
- Dispatchable Power & Ancillary Services
- Cislunar Propulsion Services
- Kilowatt scale services

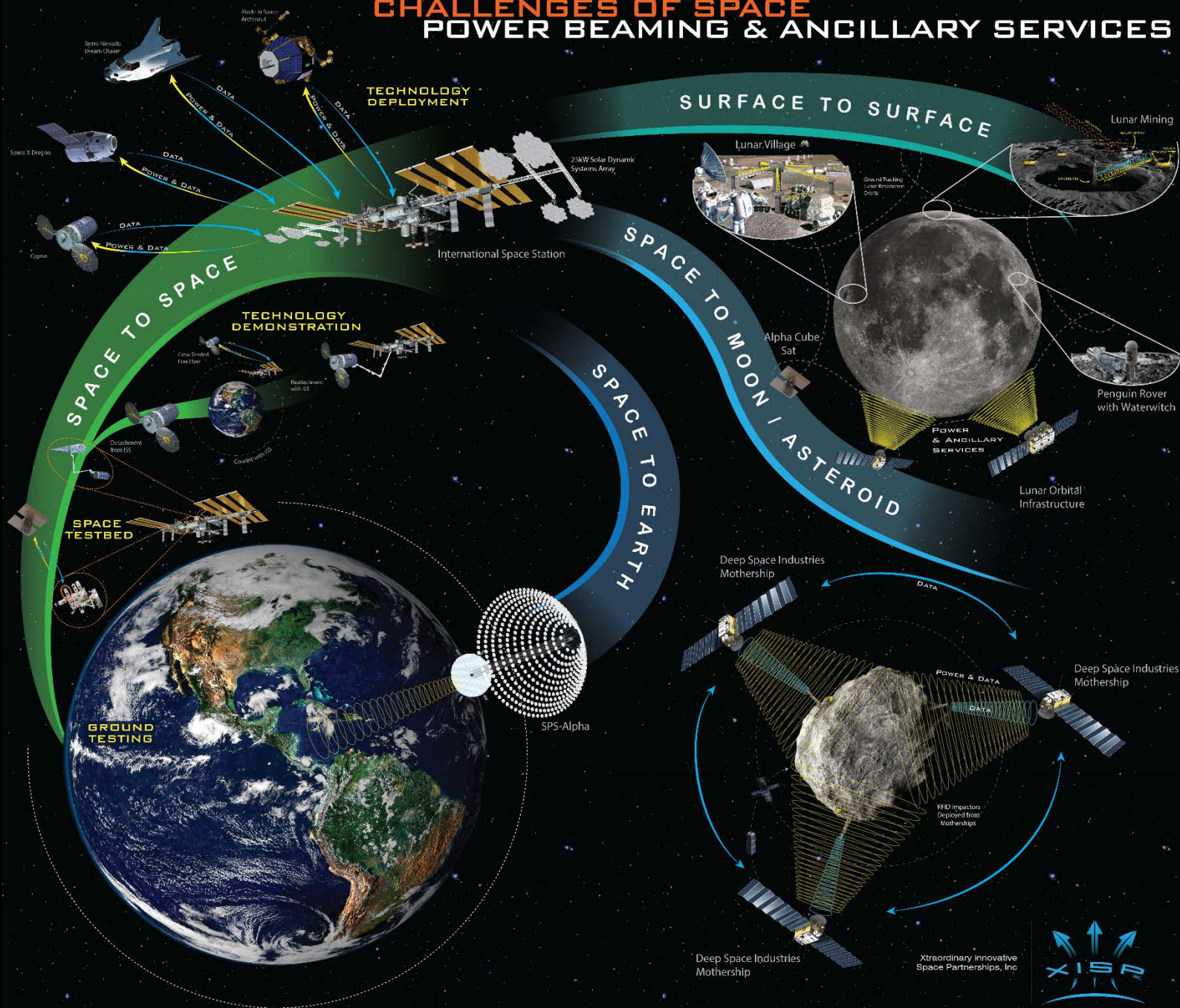
- Dispatchable Power & Ancillary Services
- 24x7 Operations Support
- Kilowatt to Megawatt Scale Services

- Synergistic impact of Cislunar Development
- Dispatchable Power & Ancillary Services
- 24x7 Operations Support
- Megawatt to Gigawatt Scale Services

- Synergistic impact of Cislunar Development
- Dispatchable Power & Ancillary Services
- National and International Geopolitical High Ground
- Gigawatt to Terawatt Scale Services



# CHALLENGES OF SPACE POWER BEAMING & ANCILLARY SERVICES



# Space-to-Space Power Beaming (SSPB)

Technology Development, Demonstration, and Deployment (TD<sup>3</sup>) Mission

XISP-Inc has hypothesized that unbundling/disaggregating power systems (i.e. the separation of power generation, transmission, control, storage, and loads) can:

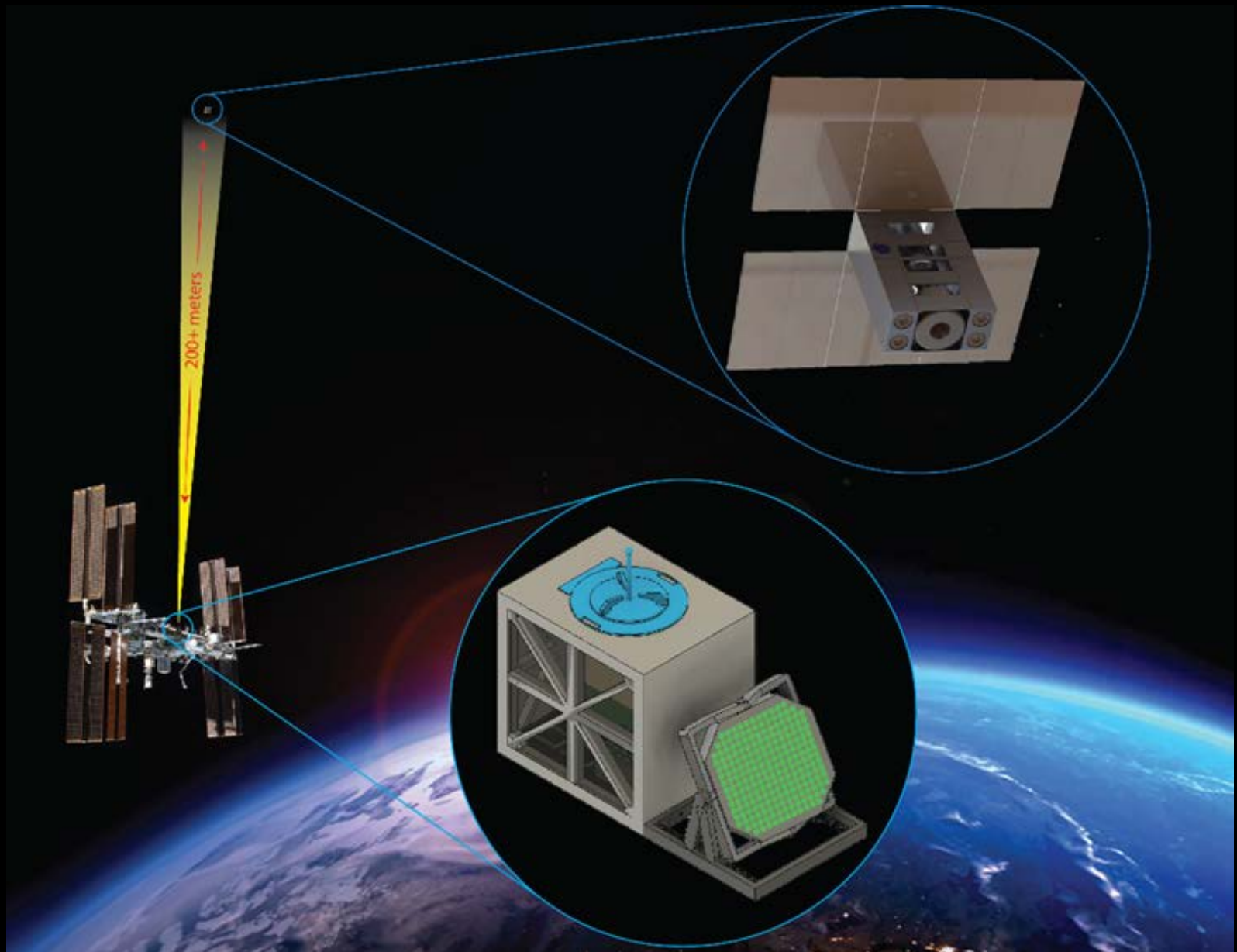
- reduce spacecraft complexity, mass and/or volume
- allow reallocation of spacecraft mass and/or volume
- alter the cadence of spacecraft mission operations
- reduce or eliminate solar pointing requirements
- impart additional delta-V to spacecraft/debris
  - indirectly (power augmentation)
  - directly (momentum transfer)

-



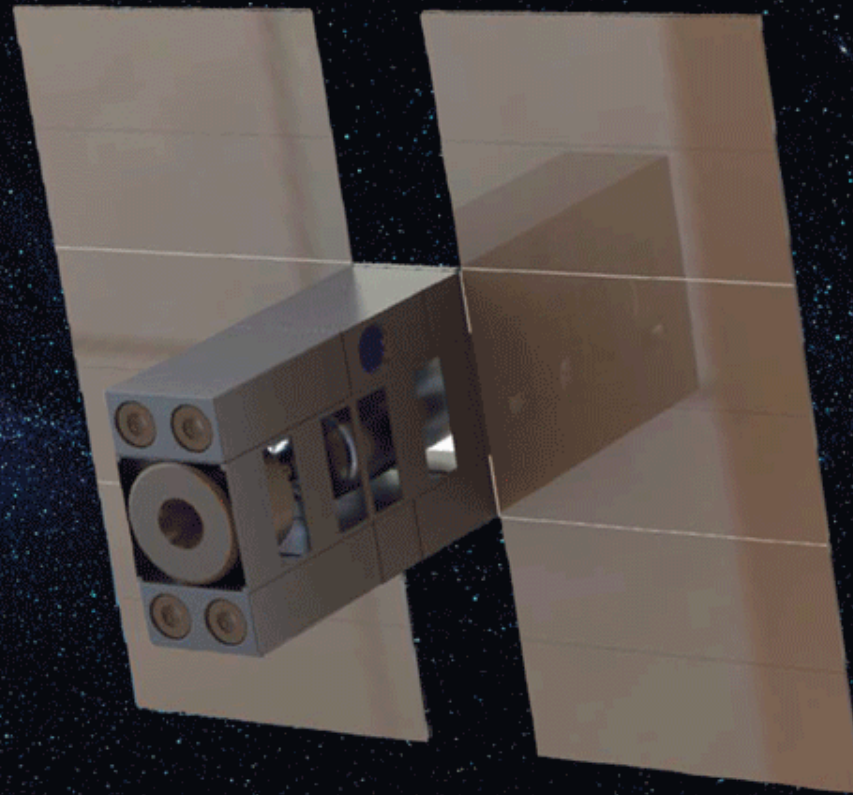


# SSPB Mission Overview

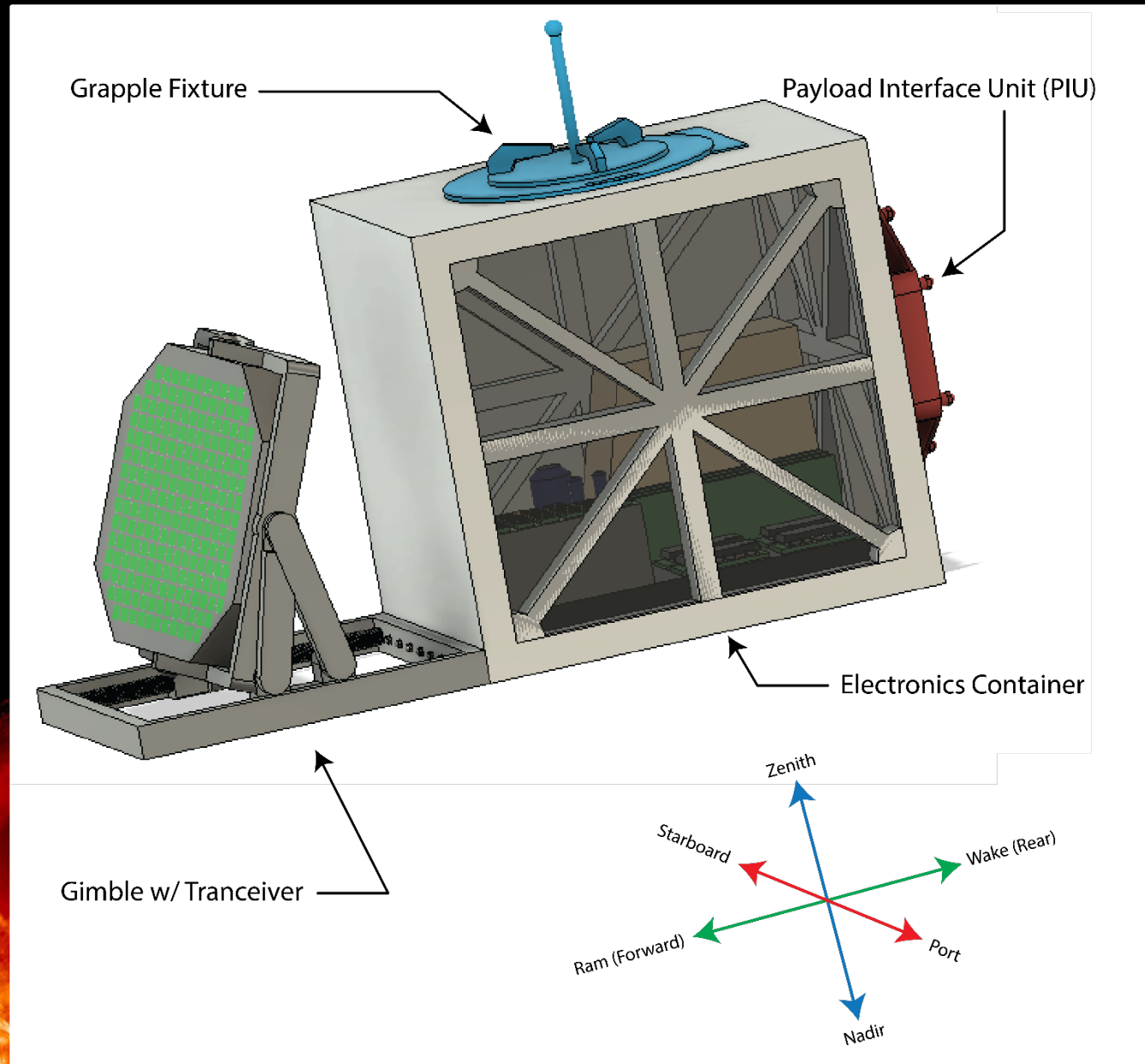




# SSPB Mission Overview



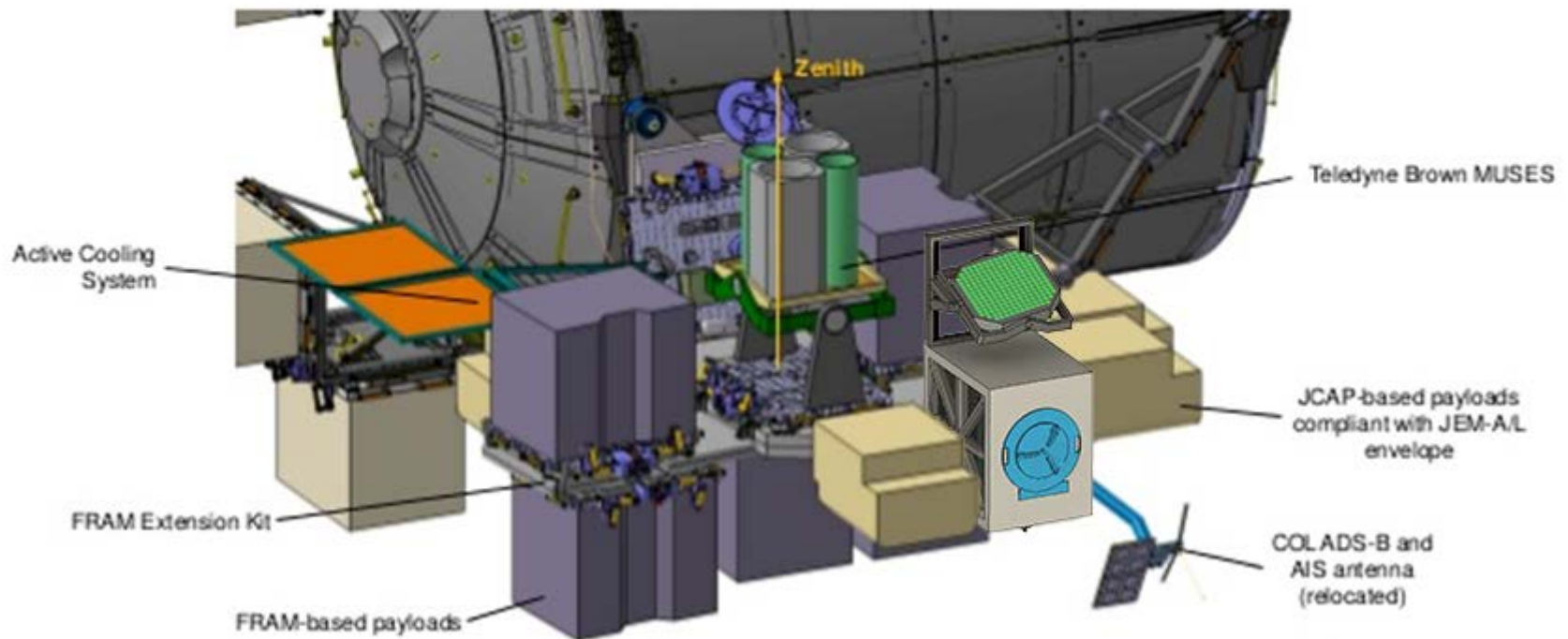
# SSPB Transceiver Preliminary Design Isometric



# Barto Exposed Facility Accommodations

Commercial External Payload Hosting Facility on ISS

## Bartolomeo On-orbit Configuration (3/4)



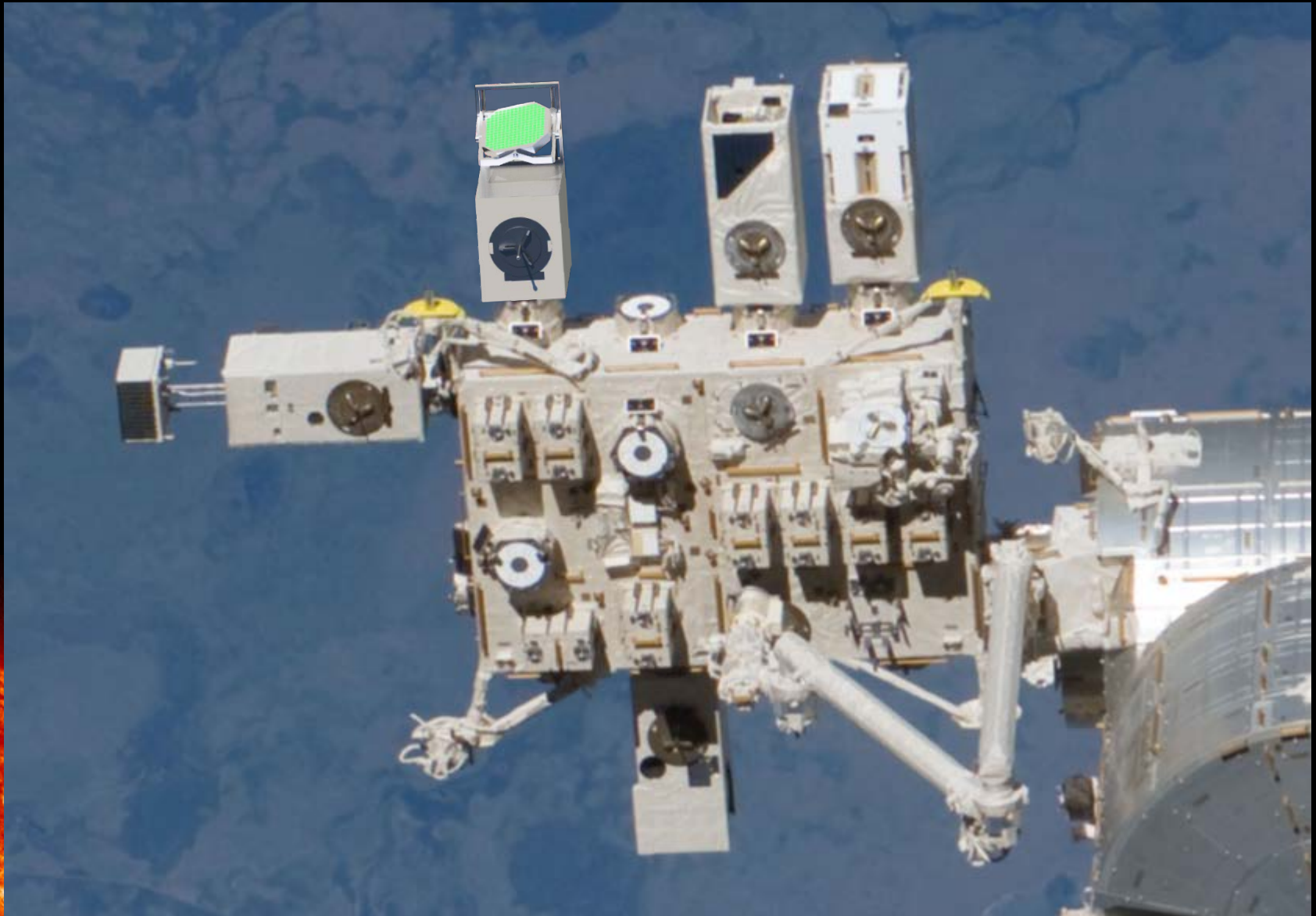
ISS PAD Conference, Presentation No. 2016-A-3, 12 July 2016

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 **AIRBUS**  
DEFENCE & SPACE



# JEM Exposed Facility Accommodations

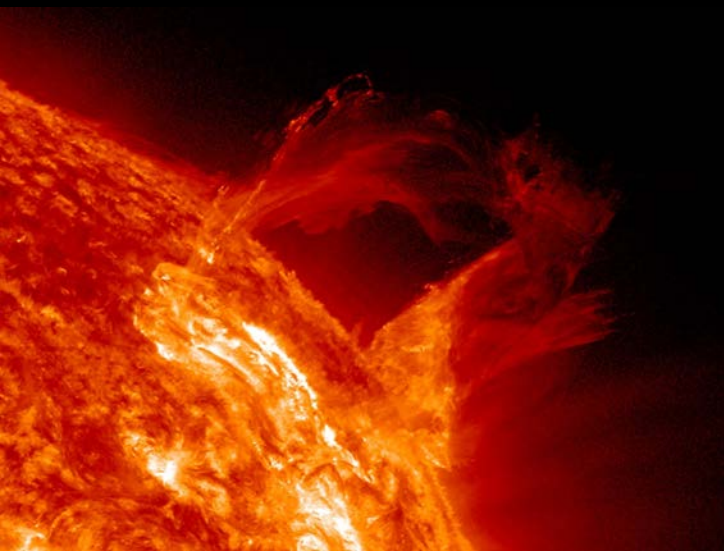


# SSPB - Mission Overview

- Unbundle/disaggregate spacecraft electrical power systems
- Provide beamed power and ancillary services as a utility
- Support further development of power beaming technology
- SSPB mission divided into three linked phases: Technology Development, Demonstration, and Deployment (TD<sup>3</sup>) intended to bridge the technology “valley of death”
- TD<sup>3</sup> mission defines a civilian non-weapons use space solar power
- Addressing real and perceived cost, schedule, and technical risks associated with Space Solar Power and ancillary services beaming
- Addressing multiple venues including: Space-to-Space, Space-to-Alternate Surfaces, as well as the potential for Space-to-Earth.
- Effort will lead to use of beamed energy to support:
  - sustained ISS co-orbiting free-flyer operations,
  - Enhanced power requirements/augmented propulsion,
  - loosely coupled modular architecture, and
  - new cluster architectures

# SSPB Phase I - Technology Development Components

- Multi-band receiving antennas (rectennas) (Ka, W, and Optical)
- Optimized Multi-band transceivers (Ka, W band, and Optical)
- Multi-band phased array transmission apertures
- Radiant energy beaming control and safety interlock system
- Water based thrusters for propulsion/active attitude control
- Power/Data/Communications/Navigation/Time Multiplexing
- Power and allied utility waveforms for Software Defined Radios
- Converged Radio Frequency & Optical SDR electronics





## SSPB Phase II - Technology Deployment Components

- Radiant energy beaming testbed (integrated evolvable/scalable power and ancillary utilities)
- Characterization of radiant energy beaming (near realtime, integrated with control)
- Optimization of radiant energy beaming (near realtime, integrated with control)
- Formulation and testing of operational rules for the use of radiant energy beaming
- CubeSat (Flight Test Article) Technology Readiness Level advancement to TRL 8/9



## SSPB Phase III - Technology Deployment Components

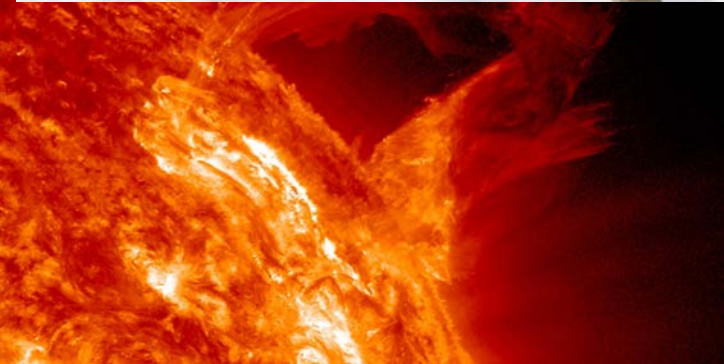
- ISS Co-orbiting Radiant Energy Beaming (200 m to 1 km)
- 6U Cubesat MSC released test with optimized transmitter & rectenna
- NGIS Cygnus pressurized logistics carrier test with optimized transmitter & rectenna
- Made In Space manufacturing protoflight rectenna (proposed)
- Evolved/scaled systems will address other markets for power and ancillary utilities delivery in LEO, MEO, HEO, GEO, Libration/Trajectory Waypoints, Lunar Orbits, and the Lunar Surface.
- Power and allied utilities delivery will progress as systems are fielded.
  - ➔ Emergency ➔ Servicing ➔ Augment ➔ Backup ➔ Primary.



# Cygnus & Dragon Free flyers



**SPACEX**





# Power Density\* versus the Solar Constant

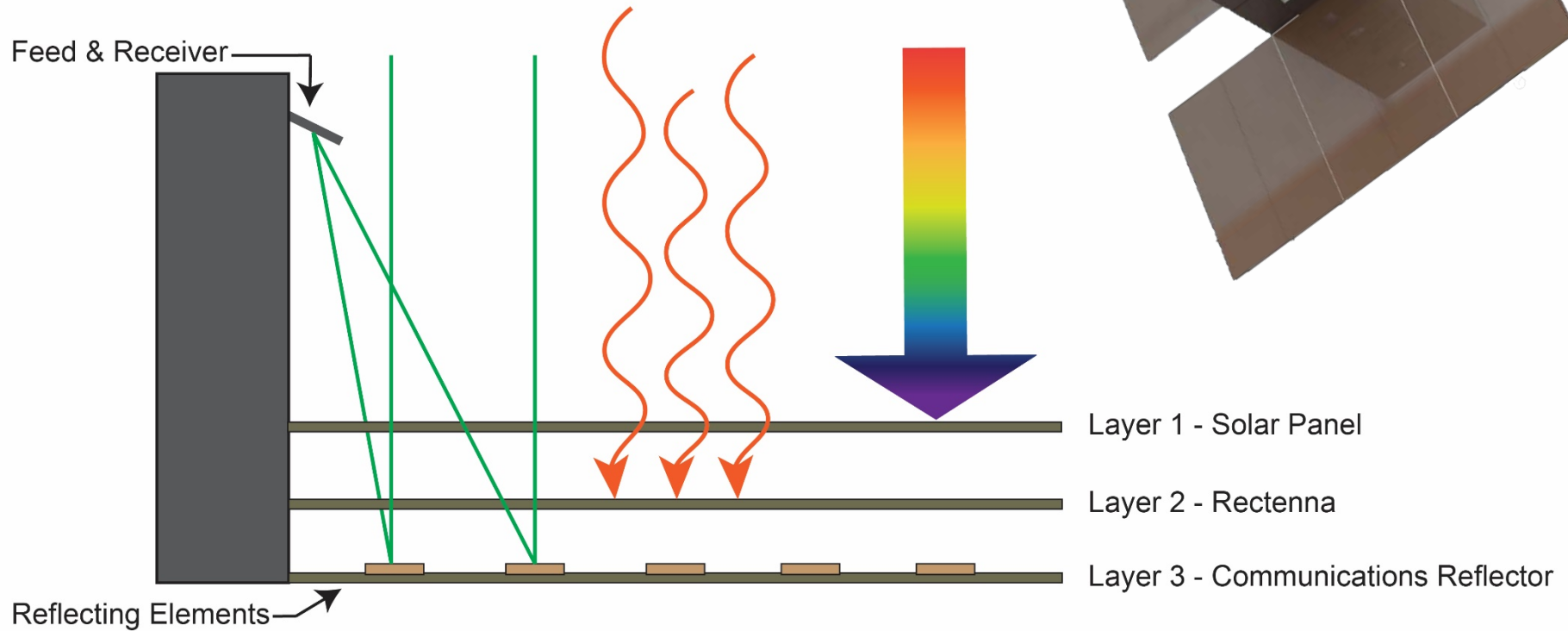
	Power Density (Watts/cm <sup>2</sup> )	Power Density (Watts/cm <sup>2</sup> )	Power Density (Watts/cm <sup>2</sup> )
	P <sub>d</sub>	P <sub>d</sub>	P <sub>d</sub>
	Case 1 @26.5 GHz	Case 2 @36 GHz	Case 3 @95 GHz
Table 1. Power Density with D=200 m, P <sub>t</sub> = 3000 W and A <sub>t</sub> = 1642 cm <sup>2</sup>	0.00964	0.01774	0.12331
Table 2. Power Density with D=200 m, P <sub>t</sub> = 6000 W and A <sub>t</sub> = 1642 cm <sup>2</sup>	0.01929	0.03549	0.24661
Table 3. Power Density with D=200 m, P <sub>t</sub> = 3000 W and A <sub>t</sub> = 10000 cm <sup>2</sup>	0.05874	0.10809	0.75108
Table 4. Power Density with D=200 m, P <sub>t</sub> = 6000 W and A <sub>t</sub> = 10000 cm <sup>2</sup>	0.11747	0.21617	1.50216
$I_{sc} = \text{Solar Constant at 1 AU} = 0.1367 \text{ Watts/cm}^2$	P <sub>d</sub> significantly lower than I <sub>sc</sub>		
	P <sub>d</sub> similar to I <sub>sc</sub>		
	P <sub>d</sub> significantly higher than I <sub>sc</sub>		
Table 5. Comparing Beaming Power Density and the Solar Constant			

\*Barnhard, Gary Pearce Space-to Space Power Beaming  
AIAA Space 2017

**Communications**  
Receiving & Transmitting

**Microwaves**  
Receiving Only (Power)

**Visible Light**  
Receiving Only (Power)

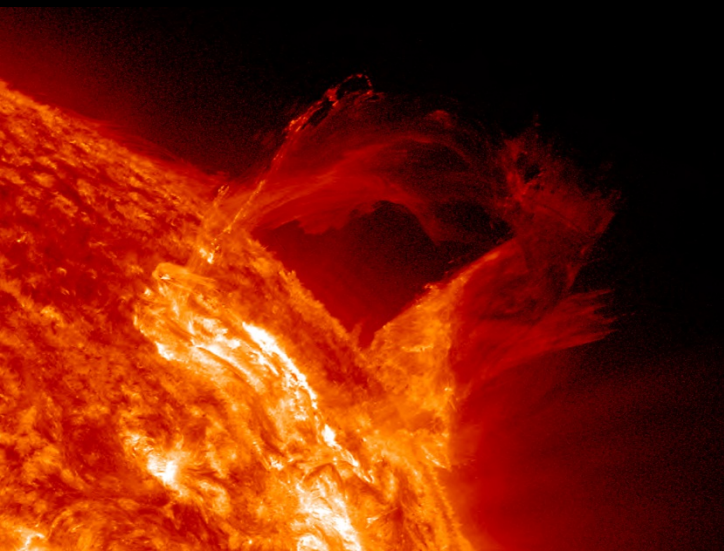


# Conclusion

- SSPB has transitioned from a conceptual mission pregnant with opportunity to a commercial mission with recognized standing.
- There is now a defined confluence of interests biased toward successful execution of the mission as public private partnership.
- Successful demonstration of space solar power beaming will:
  1. Reduce the perceived cost, schedule, technical risk of SSP
  2. Pave the way for SSP use in space-to-space, space-to-lunar/infrastructure surface, and space-to-Earth
- Commercial space applications include:
  1. enabling expansion of operational mission capabilities,
  2. enhanced spacecraft/infrastructure design flexibility, and
  3. out-bound orbital trajectory insertion propulsion, and
  4. pave the way for the Lunar Power & Light Company.

***Don't wait for the future, help us make it!***

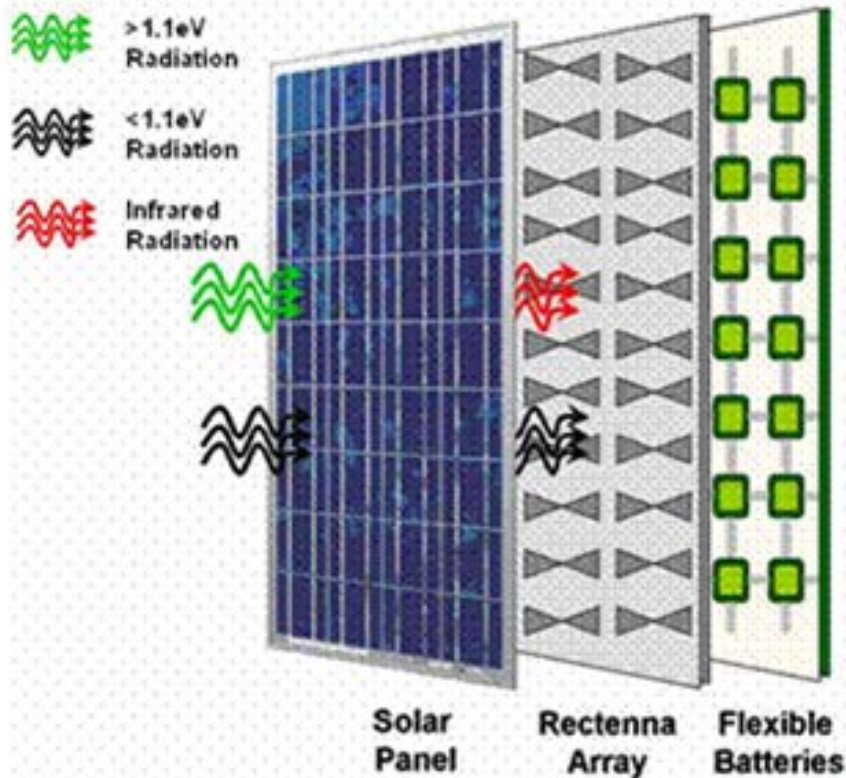
# Backup Slides





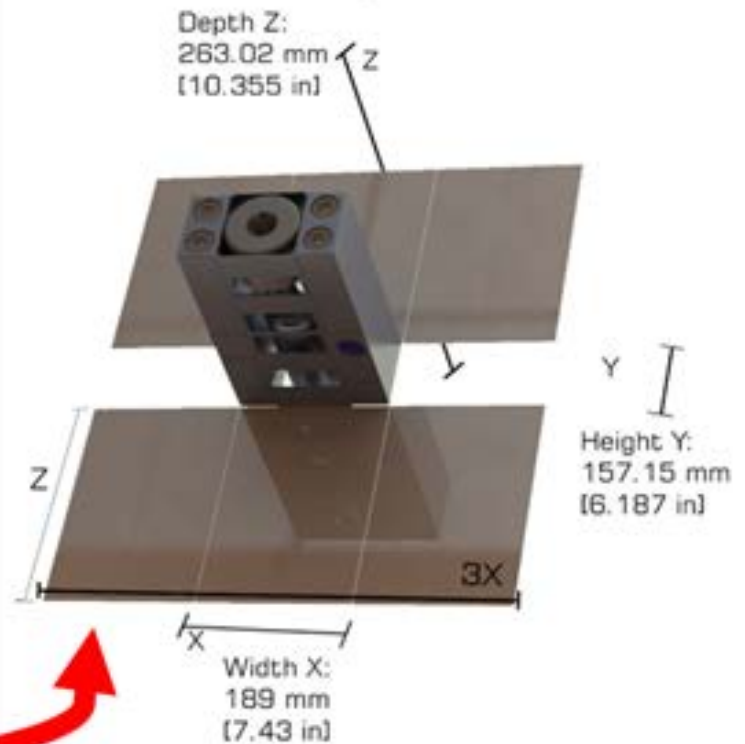
# SSPB Flight Test Article Rectenna

Reflectarray technology layers solar, rectenna, and RF Tx/Rx arrays; and possibly batteries



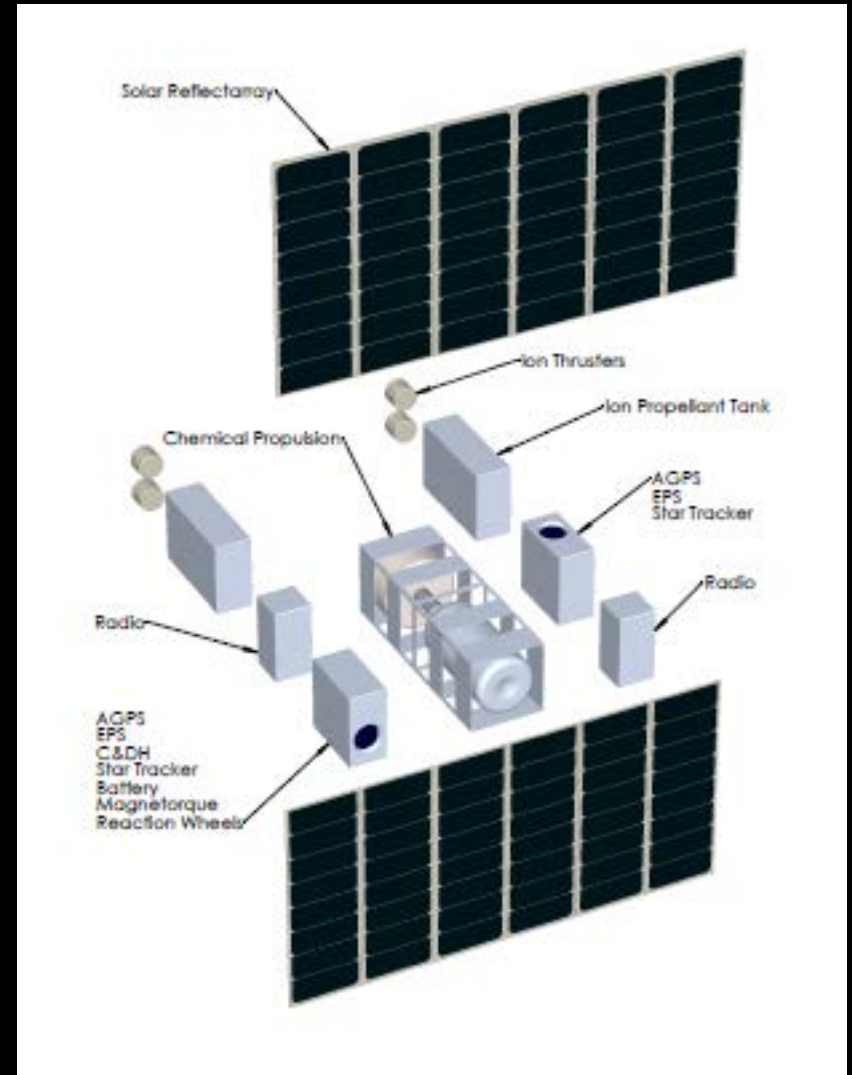
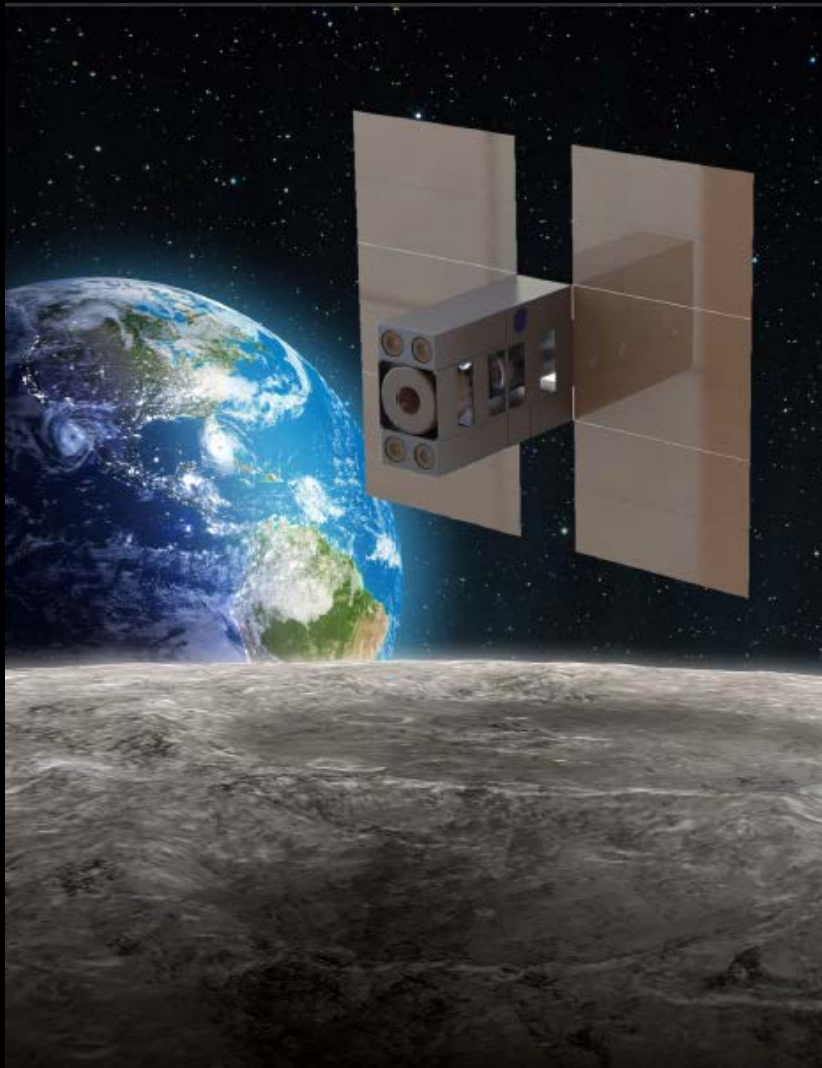
SSPB Flight Test Article is similar to Alpha Cube Sat (ACS) PDR Design

Team AlphaCubeSat  
6U Dimensional Drawing



Mass: 4.49 kg [9.89] lb

# Alpha CubeSat Derived Flight Test Articles\*



\* Alternate 6U flight test article concept derived from NASA CubeQuest Challenge Team Alpha CubeSat design

# SSPB ISS Transceiver Design Heritage



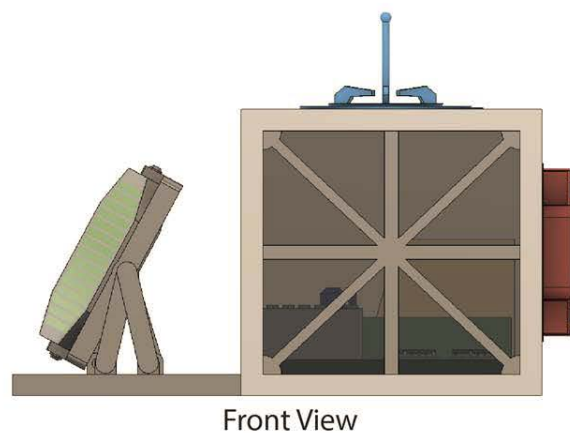
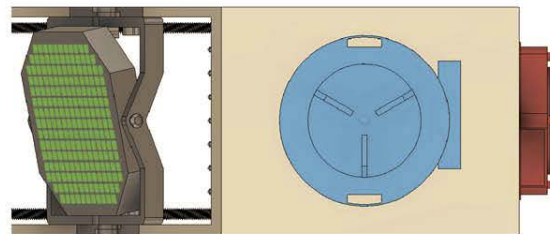
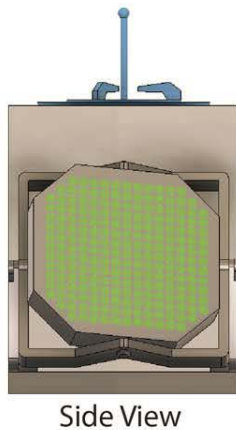
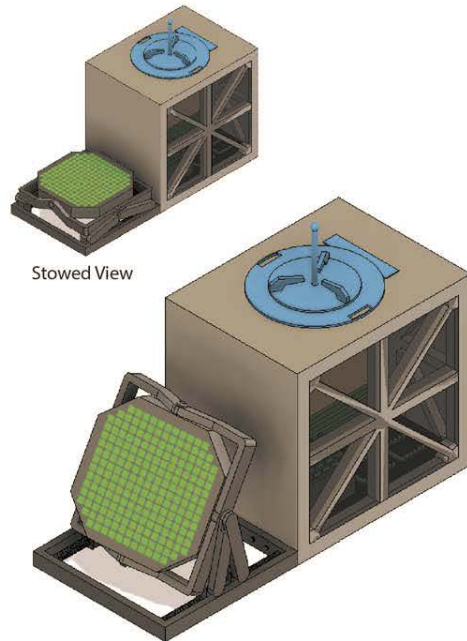
JAXA Inter-orbit  
Comm System (ICS-EF)



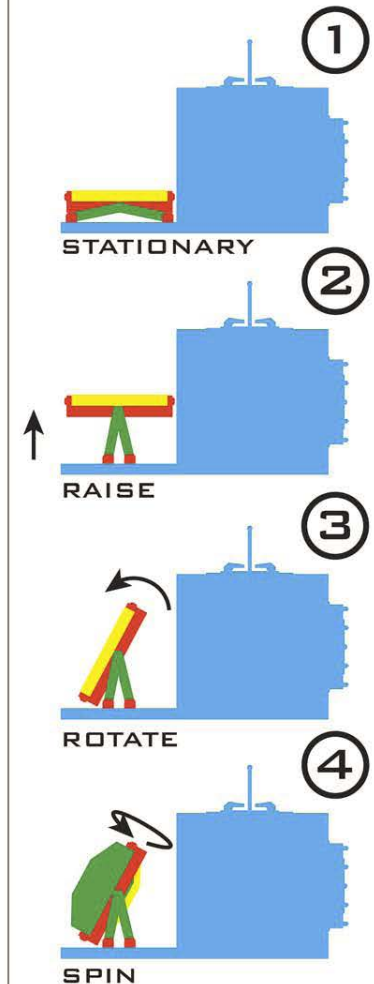
Terrestrial 95 GHz Transmitter  
(AFRL / Raytheon Design)



# SSPB Transceiver Preliminary Design Mechanicals

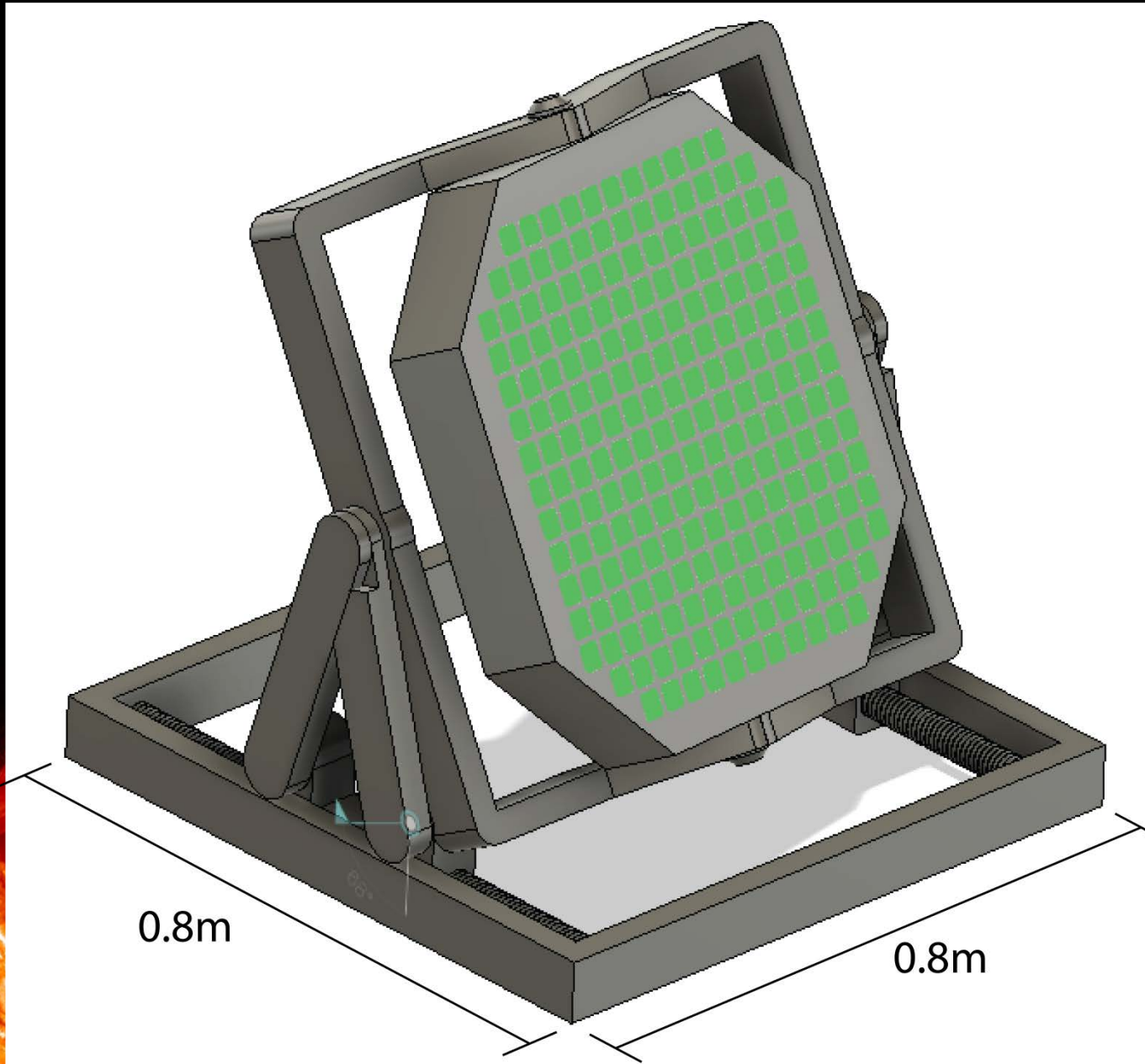


## ACTUATION





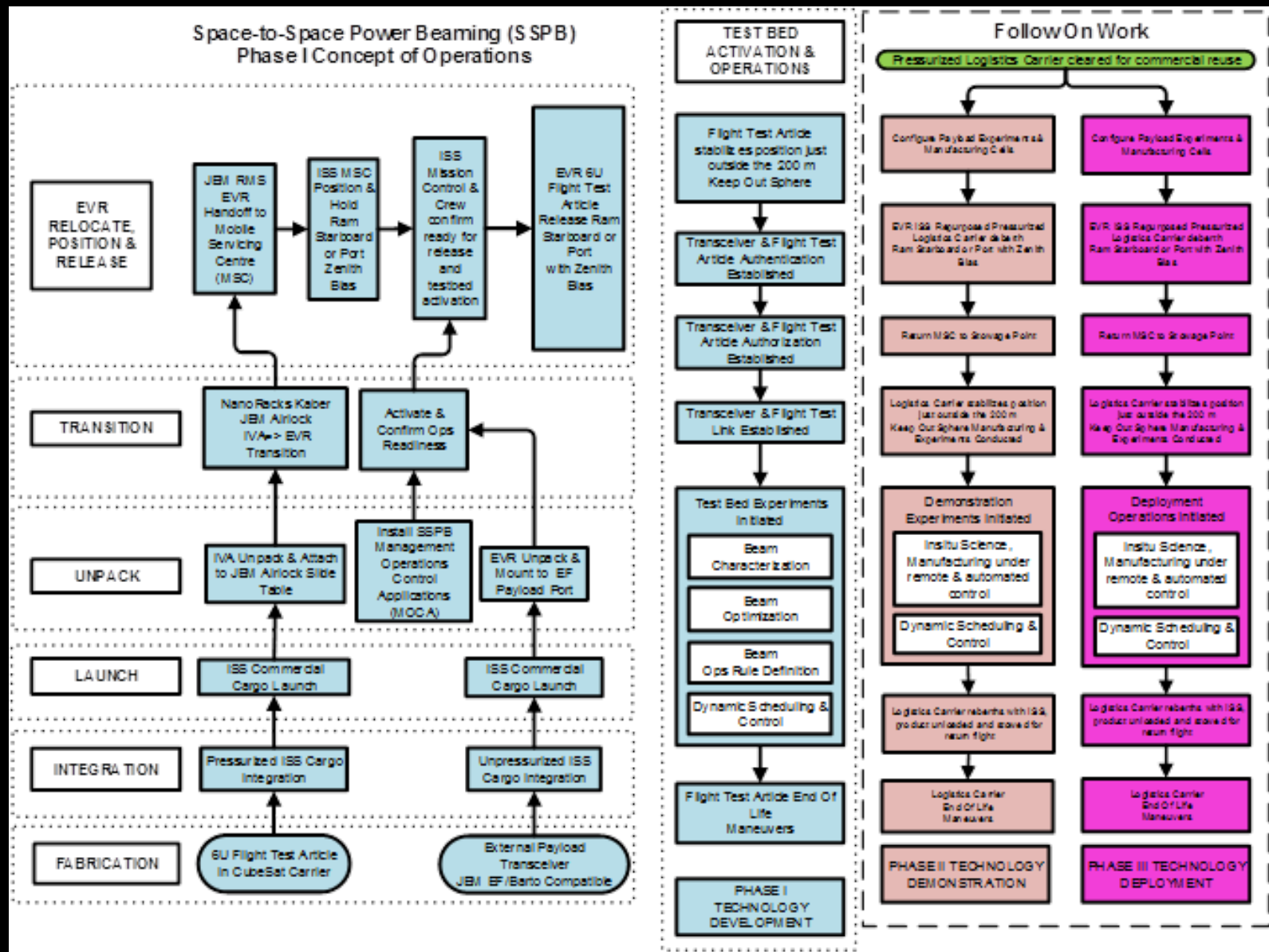
# SSPB Transceiver Preliminary Design Phased Array



# JEM & Bartolomeo Exposed Facility Accommodations

	ISS Transceiver	6U Flight Test Article	Cygnus
Payload Accommodation Type	Bartolomeo: Double Payload (Barto); Standard EF Payload (JEM EF)	Not Applicable	Not Applicable
Launch Type	Unpressurized Cargo	Pressurized or Unpressurized Cargo	Pressurized Logistics Carrier
Field of View	Ram and Zenith, gimballed phased array aperture	Station facing with active attitude control system from Ram, Starboard/Port, with Zenith Bias co-orbit > 200 m from ISS center of mass (NASA recommended location for maximum safe dwell time with active attitude control and Min Required distance based on ISS Keep Out Sphere)	Station facing with active attitude control system from Ram, Starboard/Port, with Zenith Bias co-orbit 1 to 10 km from ISS center of mass (NASA recommended location for maximum safe dwell time with active attitude control and Min Required distance based on ISS Keep Out Sphere)
Geometric Envelope Dispenser	Not Applicable	Planetary Systems Canisterized Satellite Dispenser (CSD) 402.1 x 263.53 x 157.66 mm (CSD Spec)	402.1 x 263.53 x 157.66 mm (equivalent to CSD Spec)
Geometric Envelope Payload	1000 x 800 x 1600 mm	365.9 x 239.4 x 109.7 mm (CSD Spec)	365.9 x 239.4 x 109.7 mm (equivalent to CSD payload Spec)
Mass of Dispenser	Not Applicable	4.50 kg +/- 3% (CSD Spec)	4.50 kg +/- 3% (CSD Spec)
Mass of Payload	450 kg max (Barto); 500kg max (JEM EF)	14.0 kg max (NASA Cube Quest Challenge limit)	~14.0 kg min (thermal requirement accommodations will increase mass)
Power	120Vdc operational power; less than 800 W max, less than 300 W nominal (Barto) less than 6000/3000 W max, less than 3000/1500 W nominal (JEM EF) ; survival power (All)	100 W received power (nominal heat rejection limit); survival power is provided by on-board solar arrays and batteries	Less than 3000/1500 W received power (Cygnus Payload Power Growth/Payload Power Nominal); survival power is provided by on-board solar arrays and batteries
Data Rate	<p>Hardwire: Access to gigabit ethernet to SSPB Storage Area Network device on ISS Payload Network throttled as necessary, TBD Mbps max operations, TBD Mbps nominal operations, TBD kbps keep alive, TBD Mbps Downlink/Uplink nominal operations (Barto); Access to gigabit ethernet to SSPB Storage Area Network device on ISS Payload Network throttled as necessary, TBD Mbps max operations, TBD Mbps nominal operations, TBD kbps keep alive, TBD Mbps Downlink/Uplink nominal operations (JEM EF)</p> <p>Wireless: Alternative WiFi/LiFi to SSPB Storage Area Network device on ISS Payload Network, TBD Mbps max operations, TBD Mbps nominal operations, TBD kbps keep alive, TBD Mbps Downlink/Uplink nominal operations (Barto); Gigabit ethernet to SSPB Storage Area Network device on ISS Payload Network, TBD Mbps max operations, TBD Mbps nominal operations, TBD kbps keep alive, TBD Mbps Downlink/Uplink nominal operations (JEM EF)</p>	Not Applicable	Not Applicable
Surface Area	less than 1 m <sup>2</sup> for transceiver	less than 1 m <sup>2</sup> for rectenna	less than 1 m <sup>2</sup> for rectenna
Payload return	Yes for one or more EVR compatible Orbital Replaceable Units, but not mandatory	No, unless retrieval becomes an available option	No, unless retrieval becomes an available option
Interface Compatibility	EVR Compatible: SSRMS, SPDM, JEMRMS, GOLD, Bartolomeo Payload, JEM EF Payload	EVR Compatible: SPDM	EVR Compatible: SSRMS, SPDM, JEMRMS

# SSPB Phase I Concept of Operations



# SSPB Mission Update – September 2018

- SSPB Paper prepared for AIAA Space 2017, published in NSS Space Settlement Journal.
- Recent SSPB presentations include: IEEE WiSEE 2017, DE S&T 2018, and ISDC 2018
- Upcoming paper presentation at IAC 2018 Bremen.
- CASIS is processing the SSPB resource allocation and mission development funding requests.
- CASIS has requested XISP-Inc to definitize all vendor quotes for SSPB Phase I.
- ISS Transceiver will be compatible with the Columbus Barto exposed facility in addition to the JEM Exposed Facility.
- Northrup Grumman Innovation Systems, Oceaneering, and AIRBUS have joined the SSPB mission development effort.
- New potential SSPB power augment customers have been identified including ViaSat.
- XISP-Inc is preparing direct SSPB funding proposals for NASA, AFRL, DARPA and DIUx
- SSPB included in Space Review published paper “A path to a commercial orbital debris cleanup, power-beaming, and communications utility, using technology development missions at the ISS.”
- XISP-Inc supported the Cislunar 1000 Lunar Propellant Mining study effort
- XISP-Inc prepared a brief on a Lunar “COTS” initiative to foster the development of Cislunar utility functional requirements and interface standards for HEOMD & ARC
- XISP-Inc INCA mission may result in cooperative NASA, NRL, AFRL projects that are synergistic with respect to the SSPB mission.



# SSPB Part of XISP-Inc Mission Set

- Space-to-Space Power Beaming (SSPB)
- Interoperable Network Communications Architecture (INCA) – (interoperable communications networks to accommodate customer ancillary utility requirements)
- Management Operations Control Applications (MOCA) – (near real-time state models, NASA ARC Mission Control Technologies OpenMCT software suite)
- Alpha Cube Sat (ACS) – (advanced cubesat design: reflectarray rectenna design, SDR, integrated avionics package, thruster/attitude control systems, virtual operations center)
- Halfway To Anywhere (HTA) – (bi-modal water and electric propulsion, Trajectory Insert Bus, low energy trajectory applications)

## XISP-Inc Evolving TD<sup>3</sup> Mission Set

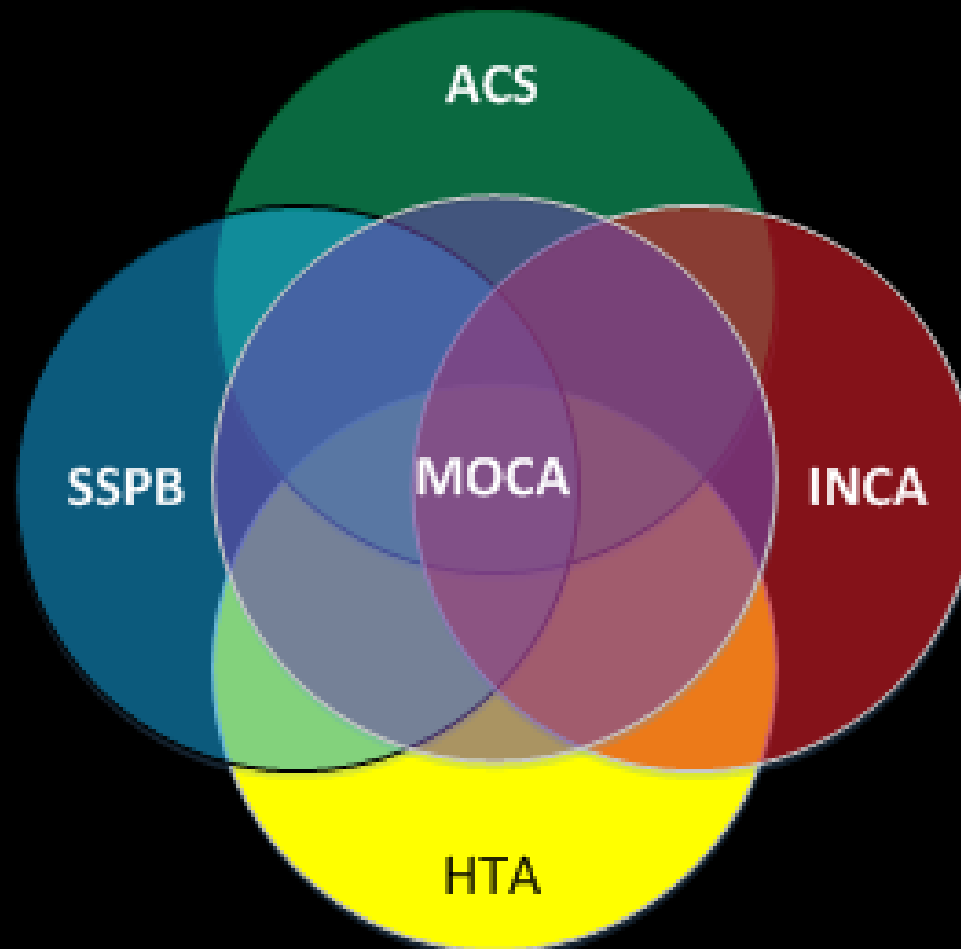
Alpha CubeSat (ACS)

Space-to-Space Power  
Beaming (SSPB)

Halfway To Anywhere  
(HTA)

Interoperable Network  
Communication  
Architecture (INCA)

Mission Operations  
Control Applications  
(MOCA)



# XISP-Inc "Follow the Resources" Mission Development Diagram

Potential  
Partners  
&  
Consortium  
Participants

.GOV

.COM

.EDU

.ORG

.NET

.IND

## Resources

Insight & Inspiration

Intellectual Property

Collaborative Environment

Facilities

Network of Contacts

Real Requirements

Technical Staff

Funding

Ground Testbed

Access to Existing  
Infrastructure

Interfaces with Existing  
Infrastructure

Space Testbed

## Evolving Web of Agreements, Proposals, and Contracts

Mission Concept:  
Definition & Development

Identify Communities of Interest

Aggregate Stranded Intellectual Property

Draw Out Requirements for Saleable  
Product

Build Something Real & Test It!

Iterate & Recurse  
as needed to  
reduce Cost,  
Schedule, and  
Technical Risk

Engage the Community of Interest:  
Research, Analyze, Document, Publish, and Present

Is the technology ready for demonstration?

YES

Is the technology ready for Deployment?

YES

**Monetize the Technology:**  
Sell it, license it, build it, and/or  
create new a new company to accomplish the same

## Technical Details -- SSPB Mission Variables

- Frequency Agnostic Transmitter w/selectable Apertures  
Ka Band → W Band → eye safe optical
- Instrumented, Optimized, and Integratable Rectennas
- Input Power Levels
- Efficiency (Piecewise & End-to-End)
- Delivered Power Levels Required
- Beaming Distance
- Ancillary Services (Comm, Data, Navigation, Time)
- Beaming Availability
- Ground, captive on-orbit, and co-orbiting testing



# SSPB Work Breakdown Structure

- Mission Development → *XISP-Inc*
- Systems Engineering → *XISP-Inc, Bus Vendor, & Consortium*
- Flight Test System Satellite Bus → *Multiple Proposals In hand*
- ISS Transmitter Frequency Agnostic SDR w/Phased Array  
Transmitter Aperture(s) → *Raytheon + Consortium teaming\**
- Flight Test System Payload “Rectenna”  
→ *Raytheon, Immortal Data + Consortium teaming*
- Integration, Verification & Validation  
→ *XISP-Inc, Bus Vendor, Raytheon, NRL, & Consortium teaming*
- Launch & ISS Accommodations  
→ *Oceaneering, AIRBUS, NGIS & NASA*
- Operations  
→ *XISP-Inc, Immortal Data, NGIS, & Consortium teaming*

*\*Consortium teaming is the internal make versus buy trade of all applicable subsystems/components/services*

# SSPB Mission Resources & Schedule

- NASA has determined\*:
  - *The XISP-Inc SSPB is classified as a Commercial Mission*
  - *Space-to-space power beaming is of interest to NASA and has the potential to affect a wide range of missions and is a potential key element of space infrastructure for the future*
  - *Overall, the [XISP-Inc SSPB] proposal is relevant to NASA's exploration goals and reflects the involvement of a team with appropriate experience.*
- NASA's level and type of participation (direct and indirect) is under review
- NASA has acknowledged and is cognizant of the formal XISP-Inc CASIS resource request being evaluated (partial mission development funding, integration, launch, ISS equipment, and ISS crew time).
  - Estimated Phase I cash & in-kind funding <\$7 Million
  - Total cash & in-kind funding < \$13 Million
  - Commercial investment is first money in
  - FY 2018 kickoff, 2019, and 2020 Phase I execution
- \* Per NASA evaluation of latest XISP-Inc SSPB ISS NRA Proposal

# SSPB Test Bed Experiments

- End-to-End & Piecewise Efficiency Optimization
  - DC ==> Microwave,
  - Beam Forming, Transmission, Rectenna
  - Microwave ==> DC
  - Advanced Development of eye safe Optical
- Transmitter & Rectenna Scalability using Cubesats
- Far/Near Field Effects & Boundaries
- Formation Flying/Alignment/Loosely Coupled Structures
- Optimization/Scaling/Efficacy of the Solution Set

*Where does it make sense to use the technology?*

# SSPB & Commercial Evolution

- Repurpose Cygnus Pressurized Logistics Carriers as crew tended co-orbiting labs with fault tolerant power and auxiliary services for some number of cycles.
- Support other co-orbiting crew-tended space manufacturing elements
- Lunar Power & Light Company – a Cislunar utility
  - Enhanced ISS power & co-orbiting community
  - LEO Independent power generation & ancillary services distribution
  - MEO/HEO/GEO power generation & ancillary services distribution
  - Libration point/lunar orbit/lunar surface power generation & ancillary services distribution



## Energy TD<sup>3</sup> Iterative and Recursive Milestones

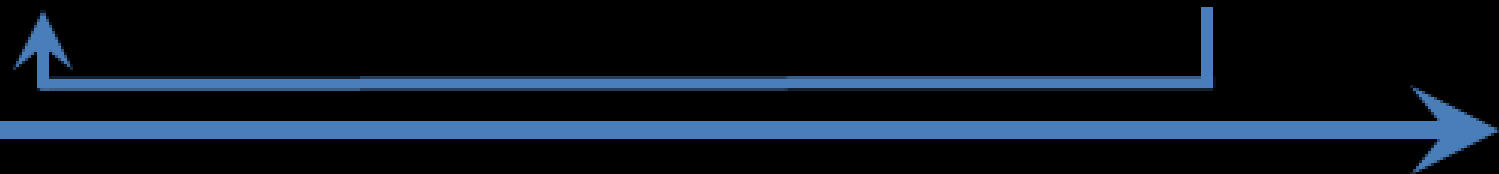
Technology  
Development



Technology  
Demonstration



Technology  
Deployment



### Space Solar Power

- Space-to-Space
- Space-to-Luna
- Space-to-Earth
- Space-to-NEO
- Space In situ
- Luna-to-Luna
- Earth-to-Earth

2019

ISS TD<sup>3</sup>

3-6 KW

SSP Testbed

NASA/DOD

Commercial

2022

LEO TD<sup>3</sup>

~100 KW

SSP LEO Demo

NASA/DOD/DOE

Commercial

2025

GEO TD<sup>3</sup>

~100 MW

SSP GEO Demo

NASA/DOD/DOE

Commercial

2029

GEO TD<sup>3</sup>

~2 GW

Full SSP

Electrical Utility

Commercial

2038

GEO TD<sup>3</sup>

10 GW

2047

SSP's >

50 GW

Co-orbiting Test

Platform Model

Spectrum Model

Orbit Slot Model

LP&L Seed/Angel

Co-orbiting Tests

ComSats Recovery

Platform TD<sup>3</sup>

Spectrum Apply

Orbit Slot Apply

LP&L Series A/B/C

Co-orbiting Labs

Lunar Test(s)

NEO Test(s)

ComSats Primary

Platform Ops

Spectrum Allocation

Orbit Slot Allocation

LP&L IPO

Co-orbiting Facilities

Lunar Operations

Asteroidal Assay

→ \$\$\$

→ \$\$\$

→ \$\$\$

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# SSPB & Commercial On-Ramps

- ISS Co-orbiting Free-flyers
  - Micro-g manufacturing cells
- Asteroidal Assay
  - Co-orbiting motherships with landed sensors
- Propulsion (delta-V augmentation)
  - Out bound & cycling spacecraft
  - Debris management
- Plug-In/Plug-Out Infrastructure Platforms
  - Communications, Navigation, Power, etc.
  - Earth facing, space operations, and space exploration
- Operational Cadence/Cycle Evolution
  - International Lunar Decade Support

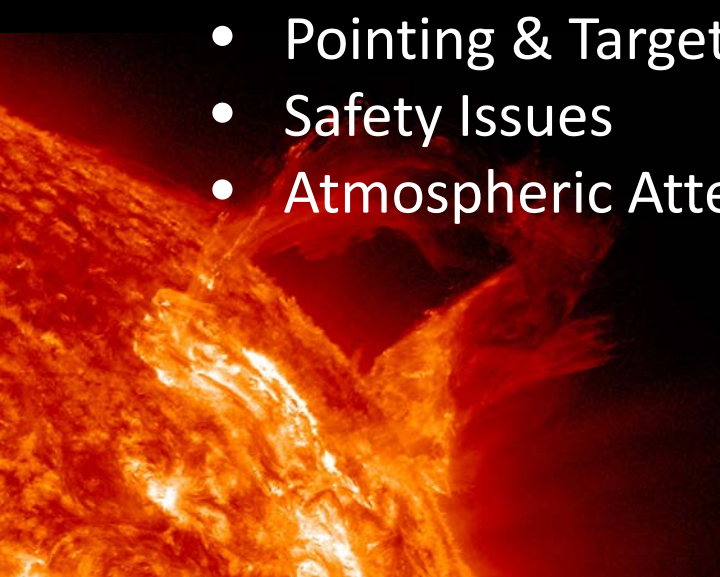
# SSPB Mathematics & Efficiency

Technologies for wireless power transmission include:

- Microwave
- Laser
- Induction

Each of these methods vary with respect to:

- End-to-End Efficiency
- Effective distance/Range
- Power handling capacity/scalability
- Pointing & Targeting Requirements
- Safety Issues
- Atmospheric Attenuation



# SSPB Microwave Efficiency Data

DC to  
Microwave  
Conversion

Beam  
Forming  
Antenna

Free Space  
Transmission

Reception  
Conversion to  
DC

**Circa 1992**  
80%–90% Efficient  
**Circa 2016**  
~95 % Efficient\*\*  
@ < 6 GHz  
10%-60%  
@ Higher Freq.

**Circa 1992**  
80 – 90 % Efficient  
**Circa 2016**  
Comparable  
@ < 6 GHz  
50%-80%  
@ Higher Freq.

**Circa 1992**  
80 – 90 % Efficient  
**Circa 2016**  
Comparable  
@ < 6 GHz  
1%-90%  
@ Higher Freq.

**Circa 1992**  
80 – 90 % Efficient  
**Circa 2016**  
~95 % Efficient\*\*  
@ < 6 GHz  
37%-72%  
@ Higher Freq.

Theoretical Maximum Possible DC to DC Efficiency

Circa 1992 ~76%

Circa 2016 85-95%\*\*\* @ < 6 GHz and TBD @ Higher Frequencies

Experimental DC to DC Efficiency Circa 1992 ~54 %, Circa 2016 TBD but significantly higher

\*William C. Brown, Life Fellow, IEEE, and E. Eugene Eves, Beamed Microwave Power Transmission and its Application to Space, IEEE Transactions On Microwave Theory and Techniques, Vol. 40, No. 6. June 1992

\*\*depending on voltage multiplier ratio

\*\*\*using one cycle modulation instead of pulse width modulation

Current High Frequency values based on input from current researchers (see paper for references)



# SSPB Recent Fiber Laser Data

**2013** – Propagation efficiencies of 90%, at 1.2km, 3kW CW – U.S. NRL

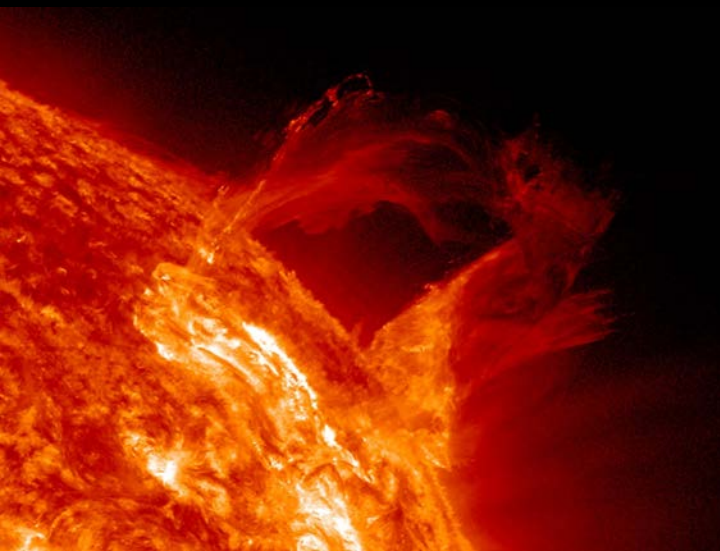
**2013** – 10kW CW individual, single-mode, fiber lasers – U.S. NRL

**2014** – 3kW three-fiber array, 80% efficiency – Northrup Grumman

**2015** – 30kW combined fiber laser mobile system fielded – Lockheed Martin & U.S. Army

**2017** – 60kW combined fiber laser mobile system fielded – Lockheed Martin & U.S. Army

*Demonstrated source power to beam  
efficiency of 43 percent*



# SSPB Recent Fiber Laser Data

**2013** – Propagation efficiencies of 90 percent, at a range of 1.2 kilometers (km), with transmitted continuous-wave power levels of 3 kilowatt (kW) – U.S. Naval Research Laboratory

**2013** – 10kW individual, single-mode, fiber lasers continuous power – U.S. Naval Research Laboratory

**2014** – Three-fiber array combining results, showing a constant 80% efficiency across a broad range of input powers (0–3000W). – Northrup Grumman Two straightforward changes appear likely to increase the combining efficiency from 80% to 90% or more. First, combining more fibers increases Diffractive Optical Element (DOE) diffraction efficiency, leading to greater combining efficiency as well as higher combined power. We successfully fabricated DOEs with fiber channel counts ranging from 9–81, leading to diffraction efficiencies of 97–99%, compared with only 92% for our three-fiber DOE. Second, standardizing the design of the fiber amplifiers would reduce losses arising from mode field and power mismatches and should also be relatively simple.

**2015** – 30kW combined fiber laser mobile system fielded – Lockheed Martin & U.S. Army

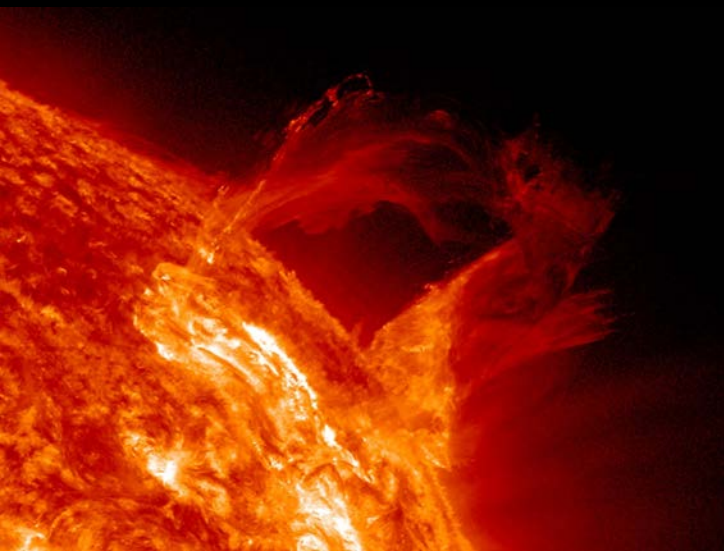
**2017** – 60kW combined fiber laser mobile system fielded – Lockheed Martin & U.S. Army

*Demonstrated source power to beam efficiency of 43 percent*

# SSPB Mathematics & Efficiency

## Theoretical Limits & Other Considerations

- Diffraction
- Thermal capacity/heat tolerance
- Electromagnetic Environment
- Navigating Frequency Allocation & Use Issues



# Mathematics of Power Beaming\* - Power Density

$$p_d = \frac{A_t P_t}{\lambda^2 D^2}$$

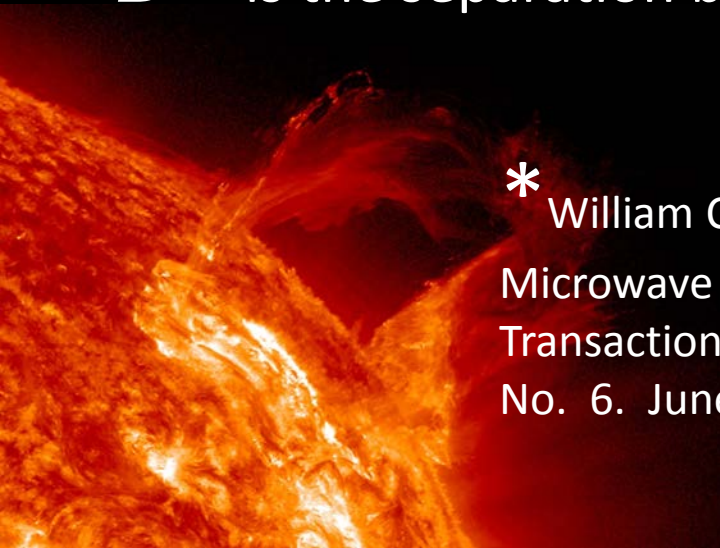
$p_d$  is the power density at the center of the receiving location

$P_t$  is the total radiated power from the transmitter

$A_t$  is the total area of the transmitting antenna

$\lambda^2$  is the wavelength squared

$D^2$  is the separation between the apertures squared



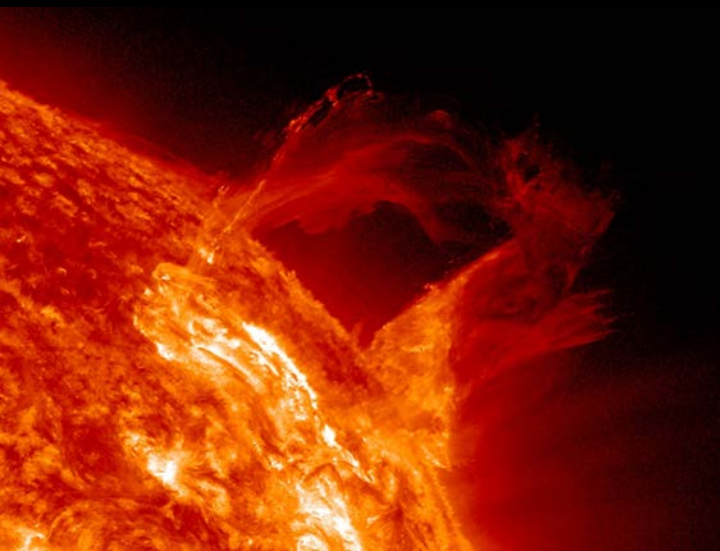
\* William C. Brown, Life Fellow, IEEE, and E. Eugene Eves, Beamed Microwave Power Transmission and its Application to Space, IEEE Transactions On Microwave Theory and Techniques, Vol. 40, No. 6. June 1992



# Mathematics of Power Beaming\* - Power Received

In cases where the rectenna aperture is not small in proportion to the transmitter aperture, transmitter power levels are high, and the frequency is high, power received ( $P_r$ ) calculations break down using the far-field equations.

Accordingly, the  $P_r$  is calculated using the collection efficiency method instead of the far-field equations.



\*Hansen, R.C.; McSpadden, J.; Benford, J.N.; "A Universal Power Transfer Curve", IEEE Microwave and Wireless Components Letters, Vol. 15, No. 5, May 2005

Barnhard, Gary Pearce Space-to Space Power Beaming AIAA Space 2017

# Power Density\* - More Optimal Solutions

**CASE 1 - Space Station Ka Band Transmitter Anticipated Power Received for various rectenna areas - Ka Low 26.5 GHz**

Distance (meters)	Rectenna Area (cm <sup>2</sup> )	Wavelength (cm)	Transmitter Area (cm <sup>2</sup> )	Power Transmitted (Watts)	Power Density (Watts/cm <sup>2</sup> )	Power Received (Watts)
D	Ar	λ	At	Pt	Pd	Pr
200	100	1.13	10000	3000	0.058736	5.85
200	200	1.13	10000	3000	0.058736	11.62
200	300	1.13	10000	3000	0.058736	17.66
200	400	1.13	10000	3000	0.058736	23.28
200	500	1.13	10000	3000	0.058736	28.77
200	600	1.13	10000	3000	0.058736	35.88
200	700	1.13	10000	3000	0.058736	40.67
200	800	1.13	10000	3000	0.058736	48.06
200	900	1.13	10000	3000	0.058736	51.78
200	1000	1.13	10000	3000	0.058736	57.39
200	2000	1.13	10000	3000	0.058736	115.25
200	3000	1.13	10000	3000	0.058736	170.43
200	4000	1.13	10000	3000	0.058736	226.16
200	5000	1.13	10000	3000	0.058736	278.89
200	6000	1.13	10000	3000	0.058736	331.15
200	7000	1.13	10000	3000	0.058736	383.69
200	8000	1.13	10000	3000	0.058736	434.70
200	9000	1.13	10000	3000	0.058736	482.33
200	10000	1.13	10000	3000	0.058736	532.15

**CASE 2 - Space Station Ka Band Transmitter Anticipated Power Received for various rectenna areas - Ka 36 GHz**

Distance (meters)	Rectenna Area (cm <sup>2</sup> )	Wavelength (cm)	Transmitter Area (cm <sup>2</sup> )	Power Transmitted (Watts)	Power Density (watts/cm**2)	Power Received (Watts)
D	Ar	λ	At	Pt	Pd	Pr
200	100	0.833	10000	3000	0.108086	10.83
200	200	0.833	10000	3000	0.108086	21.46
200	300	0.833	10000	3000	0.108086	31.81
200	400	0.833	10000	3000	0.108086	42.77
200	500	0.833	10000	3000	0.108086	52.69
200	600	0.833	10000	3000	0.108086	65.36
200	700	0.833	10000	3000	0.108086	74.37
200	800	0.833	10000	3000	0.108086	86.34
200	900	0.833	10000	3000	0.108086	96.72
200	1000	0.833	10000	3000	0.108086	107.35
200	2000	0.833	10000	3000	0.108086	209.12
200	3000	0.833	10000	3000	0.108086	307.35
200	4000	0.833	10000	3000	0.108086	402.42
200	5000	0.833	10000	3000	0.108086	493.82
200	6000	0.833	10000	3000	0.108086	581.84
200	7000	0.833	10000	3000	0.108086	667.88
200	8000	0.833	10000	3000	0.108086	749.93
200	9000	0.833	10000	3000	0.108086	829.86
200	10000	0.833	10000	3000	0.108086	904.44

**CASE 3 - Optimized W Band Transmitter Anticipated Power Received for various rectenna areas W Target 95 GHz**

Distance (meters)	Rectenna Area (cm <sup>2</sup> )	Wavelength (cm)	Transmitter Area (cm <sup>2</sup> )	Power Transmitted (Watts)	Power Density (watts/cm**2)	Power Received (Watts)
D	Ar	λ	At	Pt	Pd	Pr
200	100	0.316	10000	3000	0.751082	73.92
200	200	0.316	10000	3000	0.751082	145.97
200	300	0.316	10000	3000	0.751082	217.82
200	400	0.316	10000	3000	0.751082	287.21
200	500	0.316	10000	3000	0.751082	354.59
200	600	0.316	10000	3000	0.751082	418.97
200	700	0.316	10000	3000	0.751082	482.13
200	800	0.316	10000	3000	0.751082	546.59
200	900	0.316	10000	3000	0.751082	607.21
200	1000	0.316	10000	3000	0.751082	664.77
200	2000	0.316	10000	3000	0.751082	1176.29
200	3000	0.316	10000	3000	0.751082	1562.24
200	4000	0.316	10000	3000	0.751082	1850.47
200	5000	0.316	10000	3000	0.751082	2064.54
200	6000	0.316	10000	3000	0.751082	2220.75
200	7000	0.316	10000	3000	0.751082	2329.80
200	8000	0.316	10000	3000	0.751082	2400.27
200	9000	0.316	10000	3000	0.751082	2448.70
200	10000	0.316	10000	3000	0.751082	2481.83

**Table 3. Power Received for Various Rectenna Sizes with D=200 m, P<sub>t</sub>= 3000 W and A<sub>t</sub> = 10000 cm<sup>2</sup>**

\*Power Received with P<sub>t</sub> = 3000 W and A<sub>t</sub> = 10000 cm<sup>2</sup>  
 For rectennas ranging from 100 cm<sup>2</sup> to 10000 cm<sup>2</sup>  
 Case 1 frequency = 26.5 GHz → λ = 1.13 cm  
 Case 2 frequency = 36.0 GHz → λ = .833 cm  
 Case 3 frequency = 95.0 GHz → λ = 0.316 cm

# Power Density\* - More Optimal Solutions

CASE 1 - Space Station Ka Band Transmitter Anticipated Power Received for various rectenna areas - Ka Low 26.5 GHz							CASE 2 - Space Station Ka Band Transmitter Anticipated Power Received for various rectenna areas - Ka 36 GHz							CASE 3 - Optimized W Band Transmitter Anticipated Power Received for various rectenna areas W Target 95 GHz						
Distance (meters)	Rectenna Area (cm <sup>2</sup> )	Wavelength (cm)	Transmitter Area (cm <sup>2</sup> )	Power Transmitted (Watts)	Power Density (Watts/cm <sup>2</sup> )	Power Received (Watts)	Distance (meters)	Rectenna Area (cm <sup>2</sup> )	Wavelength (cm)	Transmitter Area (cm <sup>2</sup> )	Power Transmitted (Watts)	Power Density (watts/cm**2)	Power Received (Watts)	Distance (meters)	Rectenna Area (cm <sup>2</sup> )	Wavelength (cm)	Transmitter Area (cm <sup>2</sup> )	Power Transmitted (Watts)	Power Density (watts/cm**2)	Power Received (Watts)
D	Ar	λ	At	Pt	Pd	Pr	D	Ar	λ	At	Pt	Pd	Pr	D	Ar	λ	At	Pt	Pd	Pr
200	100	1.13	10000	6000	0.117472	11.70	200	100	0.833	10000	6000	0.216173	21.65	200	100	0.316	10000	6000	1.502163	147.83
200	200	1.13	10000	6000	0.117472	23.24	200	200	0.833	10000	6000	0.216173	42.92	200	200	0.316	10000	6000	1.502163	291.94
200	300	1.13	10000	6000	0.117472	35.32	200	300	0.833	10000	6000	0.216173	63.62	200	300	0.316	10000	6000	1.502163	435.64
200	400	1.13	10000	6000	0.117472	46.57	200	400	0.833	10000	6000	0.216173	85.53	200	400	0.316	10000	6000	1.502163	574.41
200	500	1.13	10000	6000	0.117472	57.54	200	500	0.833	10000	6000	0.216173	105.38	200	500	0.316	10000	6000	1.502163	709.18
200	600	1.13	10000	6000	0.117472	71.76	200	600	0.833	10000	6000	0.216173	130.73	200	600	0.316	10000	6000	1.502163	837.94
200	700	1.13	10000	6000	0.117472	81.33	200	700	0.833	10000	6000	0.216173	148.73	200	700	0.316	10000	6000	1.502163	964.26
200	800	1.13	10000	6000	0.117472	96.12	200	800	0.833	10000	6000	0.216173	172.67	200	800	0.316	10000	6000	1.502163	1093.18
200	900	1.13	10000	6000	0.117472	103.56	200	900	0.833	10000	6000	0.216173	193.44	200	900	0.316	10000	6000	1.502163	1214.43
200	1000	1.13	10000	6000	0.117472	114.78	200	1000	0.833	10000	6000	0.216173	214.71	200	1000	0.316	10000	6000	1.502163	1329.54
200	2000	1.13	10000	6000	0.117472	230.50	200	2000	0.833	10000	6000	0.216173	418.24	200	2000	0.316	10000	6000	1.502163	2352.57
200	3000	1.13	10000	6000	0.117472	340.86	200	3000	0.833	10000	6000	0.216173	614.71	200	3000	0.316	10000	6000	1.502163	3124.48
200	4000	1.13	10000	6000	0.117472	452.33	200	4000	0.833	10000	6000	0.216173	804.84	200	4000	0.316	10000	6000	1.502163	3700.93
200	5000	1.13	10000	6000	0.117472	557.78	200	5000	0.833	10000	6000	0.216173	987.65	200	5000	0.316	10000	6000	1.502163	4129.07
200	6000	1.13	10000	6000	0.117472	662.30	200	6000	0.833	10000	6000	0.216173	1163.68	200	6000	0.316	10000	6000	1.502163	4441.50
200	7000	1.13	10000	6000	0.117472	767.38	200	7000	0.833	10000	6000	0.216173	1335.76	200	7000	0.316	10000	6000	1.502163	4659.60
200	8000	1.13	10000	6000	0.117472	869.41	200	8000	0.833	10000	6000	0.216173	1499.85	200	8000	0.316	10000	6000	1.502163	4800.55
200	9000	1.13	10000	6000	0.117472	964.66	200	9000	0.833	10000	6000	0.216173	1659.73	200	9000	0.316	10000	6000	1.502163	4897.40
200	10000	1.13	10000	6000	0.117472	1064.30	200	10000	0.833	10000	6000	0.216173	1808.88	200	10000	0.316	10000	6000	1.502163	4963.66

Table 4. Power Received for Various Rectenna Sizes with D=200 m, P<sub>t</sub>= 6000 W and A<sub>t</sub> = 10000 cm<sup>2</sup>

\*Power Received with P<sub>t</sub> = 6000 W and A<sub>t</sub> = 10000 cm<sup>2</sup>  
 For rectennas ranging from 100 cm<sup>2</sup> to 10000 cm<sup>2</sup>  
 Case 1 frequency = 26.5 GHz → λ = 1.13 cm  
 Case 2 frequency = 36.0 GHz → λ = .833 cm  
 Case 3 frequency = 95.0 GHz → λ = 0.316 cm



# Technological Challenges

- Physics of near field/ far field energy propagation understood.
- Use of radiant energy to transfer: power, data, force, &/or heat, either directly and/or by inducing near field effects at a distance, are not well understood
- Moreover, there is very limited engineering knowledge base of practical applications.
- Accordingly, this is applied engineering work, (a.k.a. technology development), not new physics.

*To optimize beaming applications we need to better understand how each of the components of radiant energy can be made to interact in a controlled manner.*



# Technological Challenges -2

- Radiant energy components include
  - Electrical
  - Magnetic
  - Linear & Angular Momentum
  - Thermal
  - Data
- There are potential direct and indirect uses for each beam component

Use of any combination of these components has implications for all spacecraft systems (e.g., power, data, thermal, communications, navigation, structures, GN&C, propulsion, payloads, etc.)

## Technological Challenges - 3

- In theory, the use of the component interactions can enable:
  - Individual knowledge of position and orientation
  - Shared knowledge loose coupling /interfaces between related objects
  - Near network control (size to sense/proportionality to enable desired control)
  - Fixed and/or rotating planar beam projections
  - Potential for net velocity along any specified vector

*In theory, there is no difference between theory and practice – but in practice, there is.*

*– Jan L.A. van de Snepscheut  
computer scientist*



## Additional Challenges - 3

- Economics

- Map the financing to terrestrial electrical power and ancillary services utility analog that just happens to be in space.
- Each addressable market has different fundamental figures of merit.

- Public/Private Partnerships

- Drawing out the confluence of interests that can support substantive agreements

- GeoPolitical

- Make International Cooperation/Collaboration real.



# The Evolving XISP-Inc Team . . .

## XISP-Inc SSPB Core Team

- Gary Pearce Barnhard, XISP-Inc
- John Mankins, Mankins Space Systems
- Seth Potter, XISP-Inc
- James McSpadden, Raytheon
- Paul Werbos
- Paul Jaffe, NRL
- Brad Blair

## Additional XISP-Inc Staff & Consultants

- Joseph Rauscher
- Brahm Segal
- Eric Dahlstrom
- Aaron Harper
- James Muncy
- David Cheuvront
- Christopher Cassell
- Alfred Anzaldua
- Jeff Greason
- Lisa Kaspin-Powell
- Gregory Allison
- Tim Cash
- Michael Doty
- Richard Smalling
- Ed Belbruno
- Dick Dickinson
- Anita Gale
- Dennis Wingo
- Ken Ford
- David Dunlop



# The Evolving SSPB Team . . .

## **Commercial Entities**

- Xtraordinary Innovative Space Partnerships, Inc. - Gary Barnhard, et al.
- Barnhard Associates, LLC - Gary Barnhard, et al.
- Raytheon, Inc. – James McSpadden, et al.
- Northrup Grumman Innovative Systems – Bob Richards, et al.
- Immortal Data Inc. – Dale Amon, et al.
- Deep Space Industries, Inc - Peter Stibrany, et al.
- Center for the Advancement of Science In Space (CASIS) – Etop Esen, et al.
- Oceaneering – Mike Withey, et al.
- Blue Canyon Technologies – George Stafford, et al.
- Made In Space, Inc. – Jason Dunn, et al.
- Tethers Unlimited, Inc. – Rob Hoyt, et al.
- Power Correction System, Inc – Brahm Segal, et al.

## **Non-profit Organizations:**

- Space Development Foundation – David Dunlop, et al.
- SPACECanada – George Dietrich, et al.
- National Space Society – Michael Snyder, et al.

# The Evolving SSPB Team . . .

## Universities:

- 1) University of Maryland Space Systems Lab – David Akin, et.al
- 2) University of New Mexico Configurable Space Microsystems Innovations and Applications Center (COSMIAC) - Christos Christodoulou, et al.
- 3) University of North Dakota Space Systems Lab – Sima Noghanian, et al.
- 4) Saint Louis University Space Systems Lab – Michael Swartwout, et al.
- 5) Michigan Technical University – Reza Zekavat, et al.
- 6) CalTech – Mike Kelzenberg

## Government Agencies:

- Naval Systems Research Lab - Paul Jaffe, et.al
- Multiple NASA Centers will have some cooperating role – NASA ARC, et.al.
- NASA Headquarters Human Exploration & Operations Mission Directorate
  - Advanced Exploration Systems Division, Jason Crusan, et.al.
  - Space Communications and Navigation Office, Jim Schier, et.al.
- Discussions underway with AFRL SpRCO

Multiple other commercial, educational, non-profit, and individual expressions of substantive interest have been received

# Next Steps

- SSPB is a XISP-Inc commercial mission recognized by NASA.
- CASIS ISS Resources, Commercial Cargo, Integration Support, and mission development investment requests are being processed.
- NASA will participate indirectly through CASIS and through one or more means accelerating and/or adding additional milestones.
- Balance of funding (cash & In-kind) will be raised from the SSPB consortium investments, and XISP-Inc debt/equity financing.
- Additional partners/participants are being sought across the commercial, academic, non-profit, and government sectors.
- Opportunities for international cooperation leveraging the ISS Intergovernmental Agreement are being developed.

*Use of ISS helps ensure that this is an international cooperative/collaborative research effort.*