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

C3 Session 2 -- Wireless Power Transmission

IAC-18-C3.2.4

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Space-to-Space Power Beaming (SSPB)

(1) The Problem Space
(2) Mission Overview
(3) Mission Concept of Operations
(4) Mission Status
(5) XISP-Inc Commercial Mission Set
(6) Mission Technology, Development, and Demonstration TD^3
(7) Mission Technical Details
(8) Amplification of challenges & opportunities
(9) Evolving the mission
(10) Conclusion

The Problem . . .

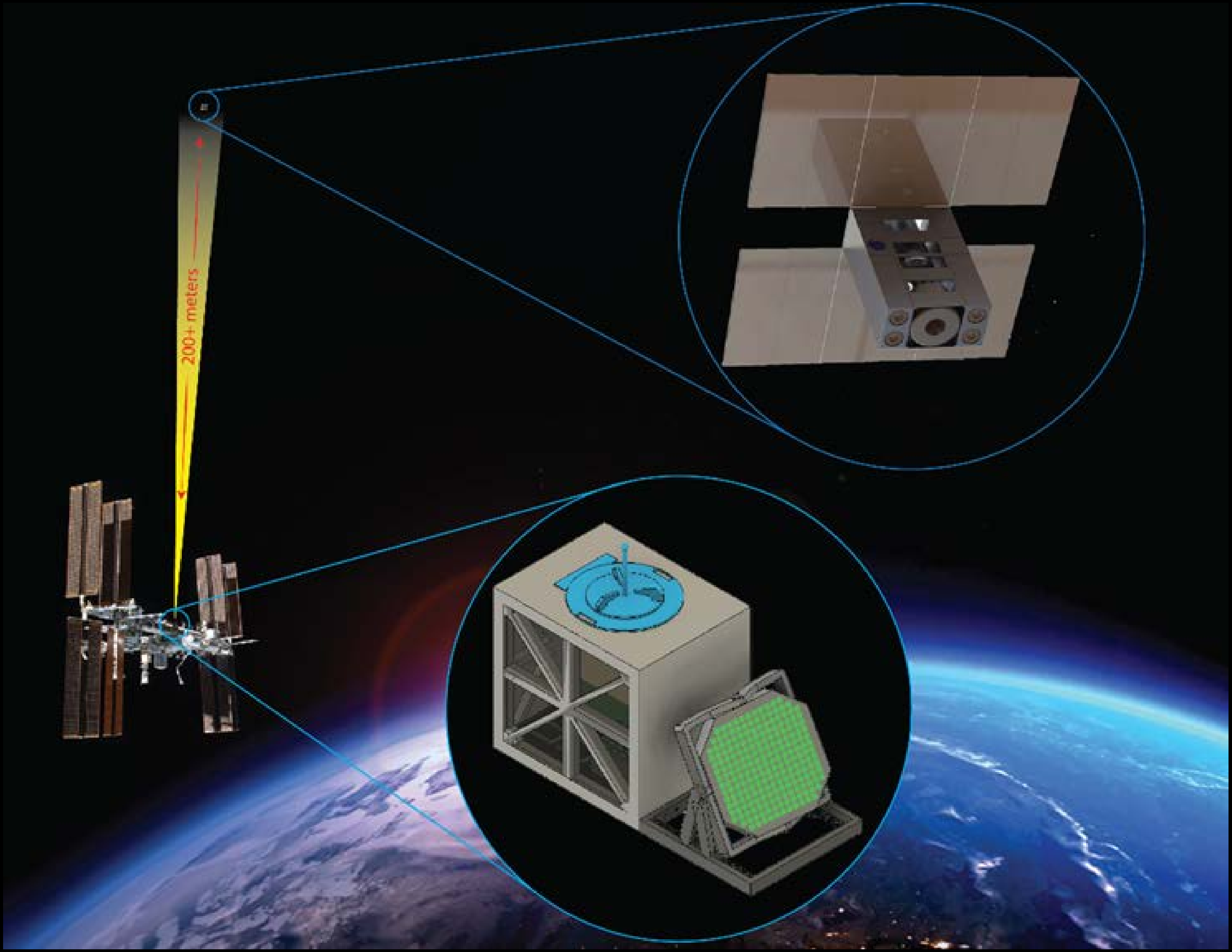
XISP-Inc has hypothesized that unbundling/disaggregating power systems (i.e. the separation of power generation, transmission, control, storage, and loads) can:

- 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)

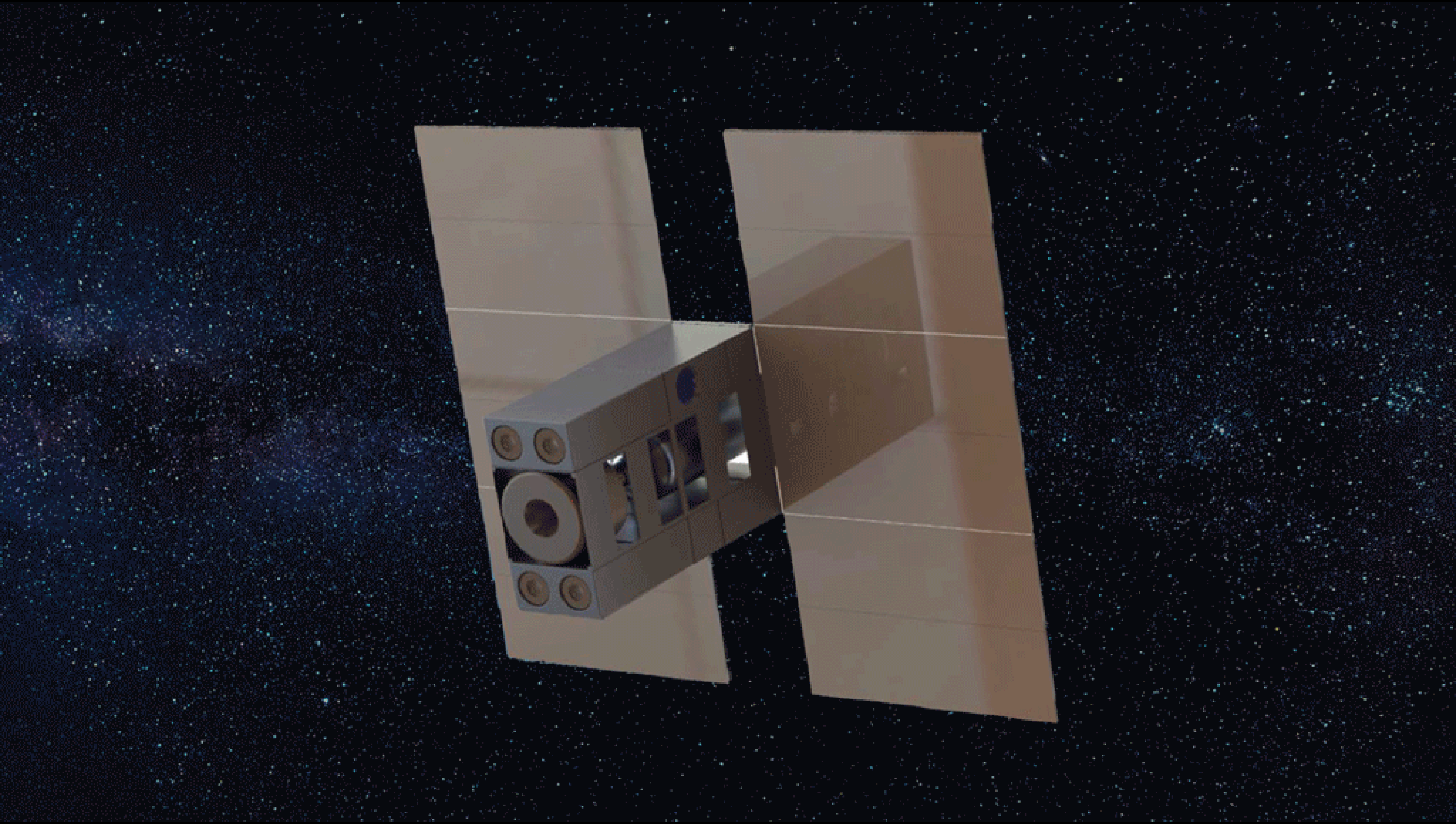
SSPB Mission Overview

- 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^3) intended to bridge the technology “valley of death”
- TD^3 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

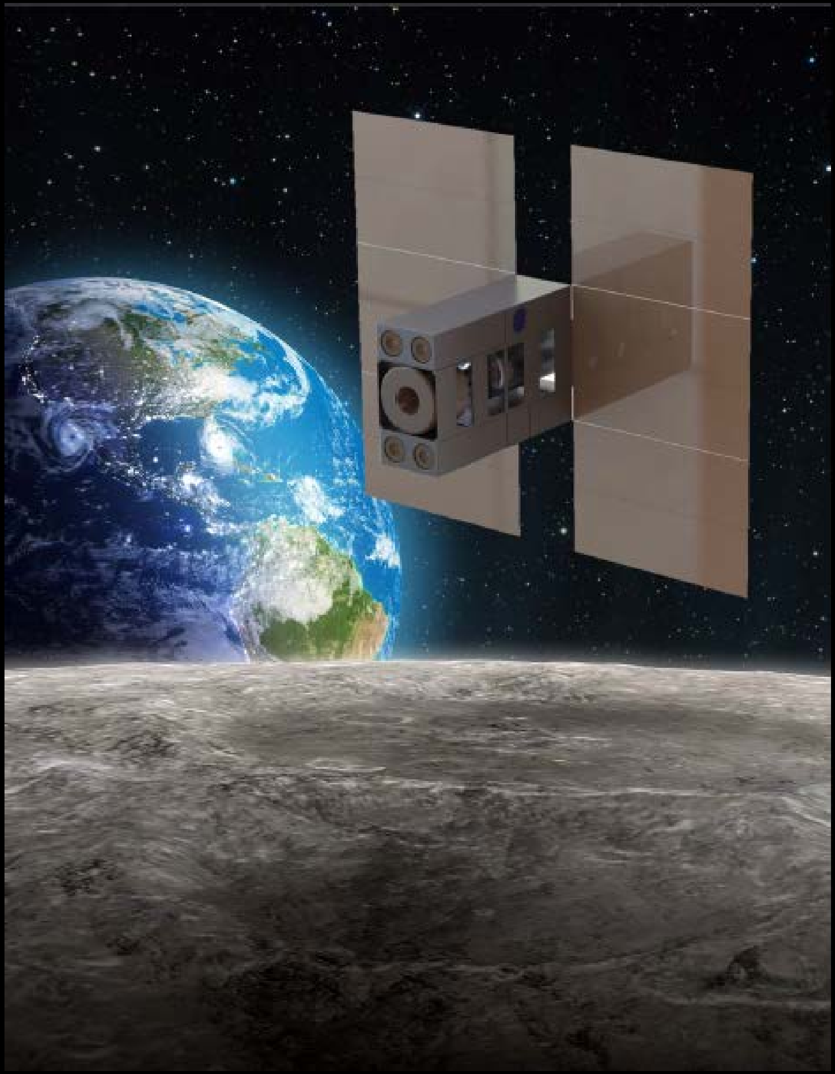
SSPB Mission Overview

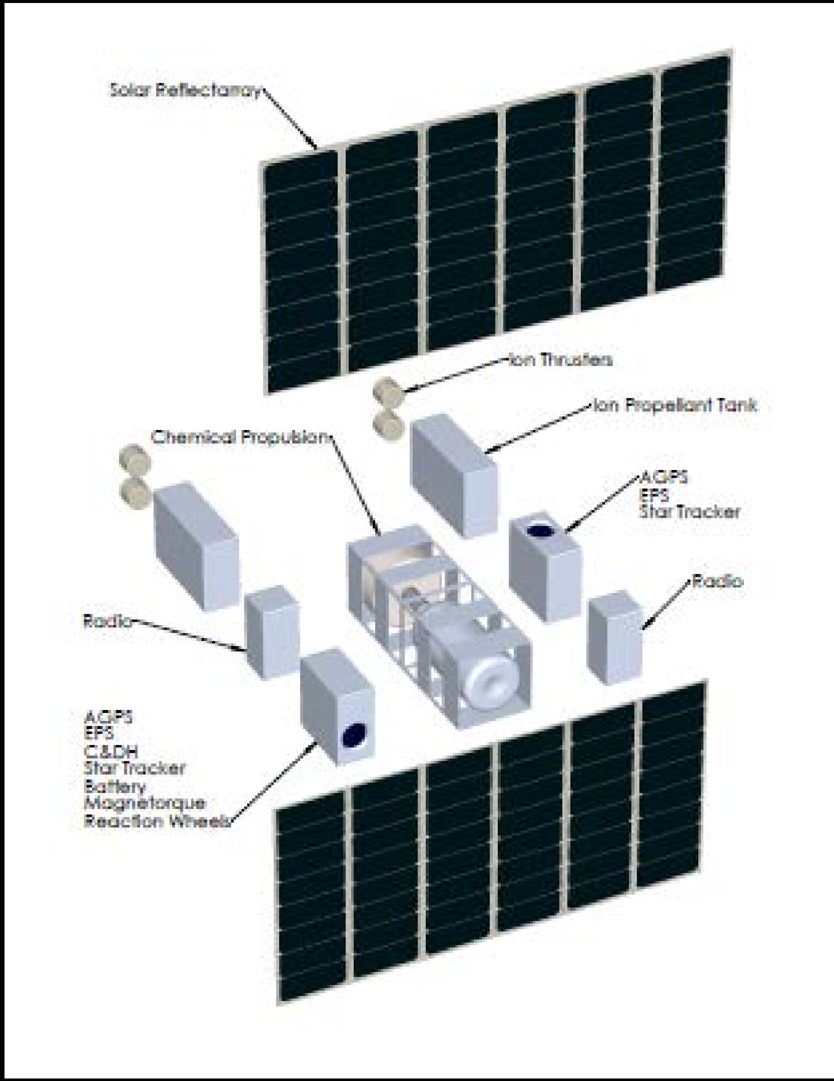


SSPB Mission Overview



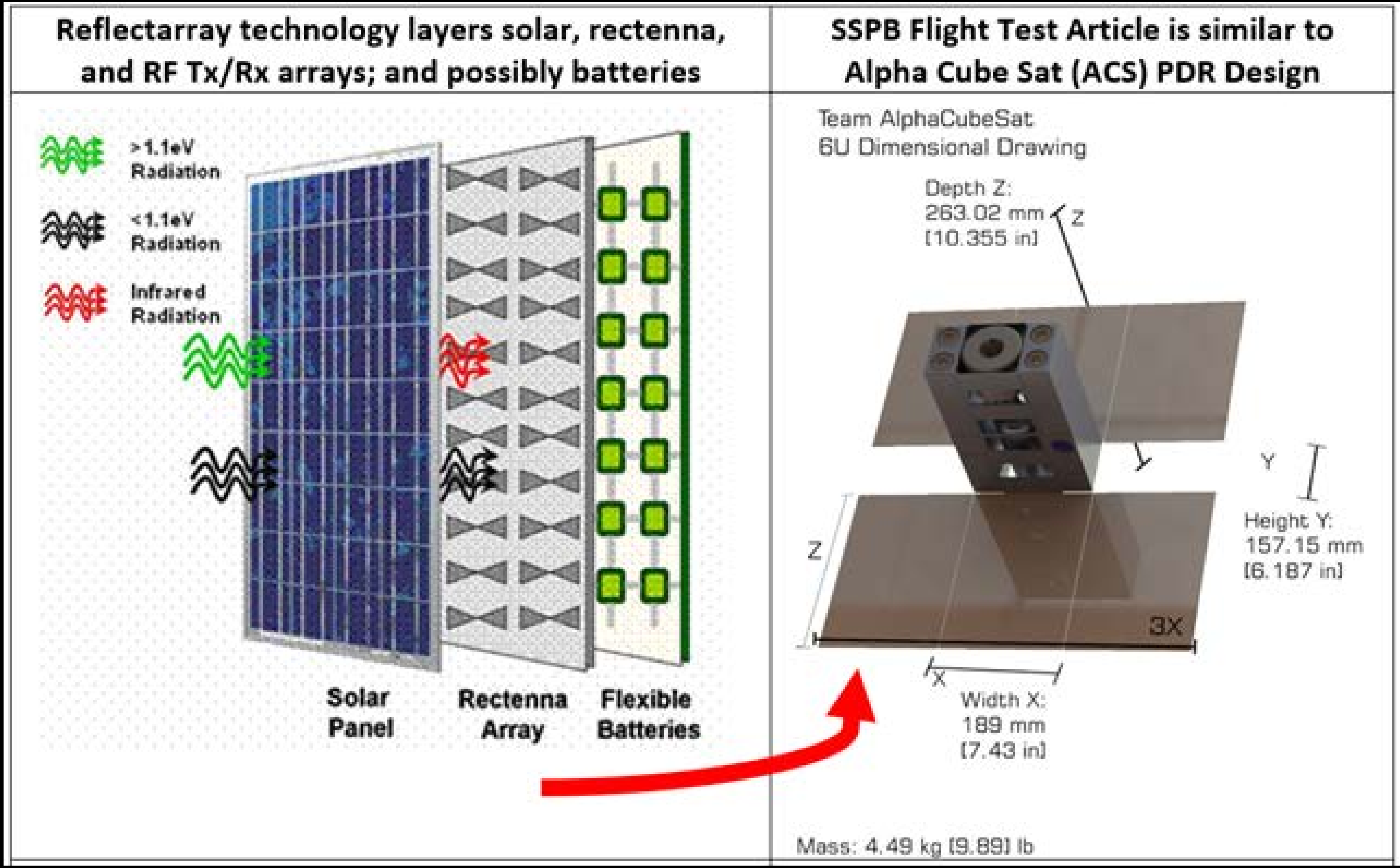
Alpha CubeSat Derived Flight Test Articles*

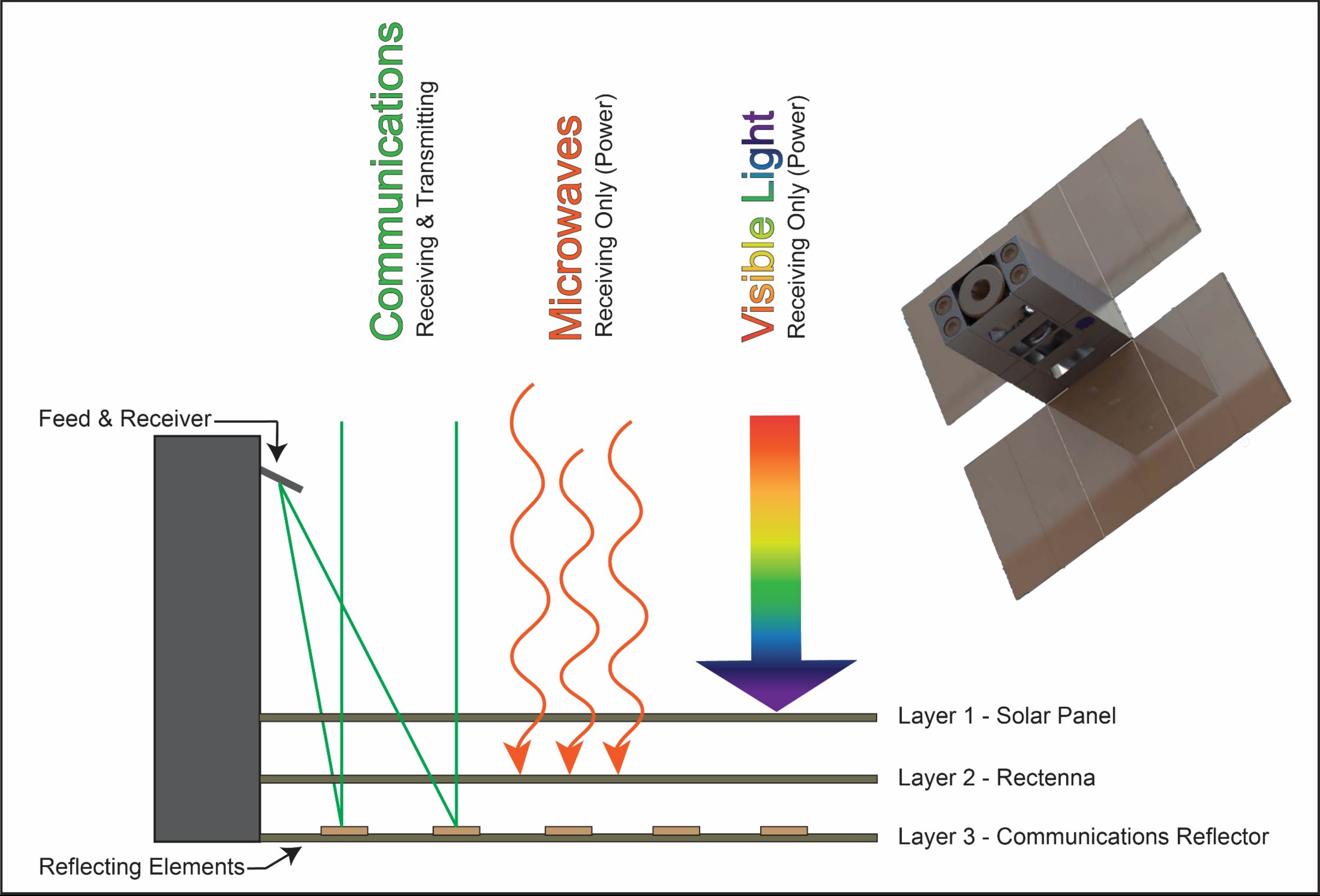




* Alternate 6U flight test article concept derived from NASA CubeQuest Challenge Team Alpha CubeSat design

SSPB Flight Test Article Rectenna



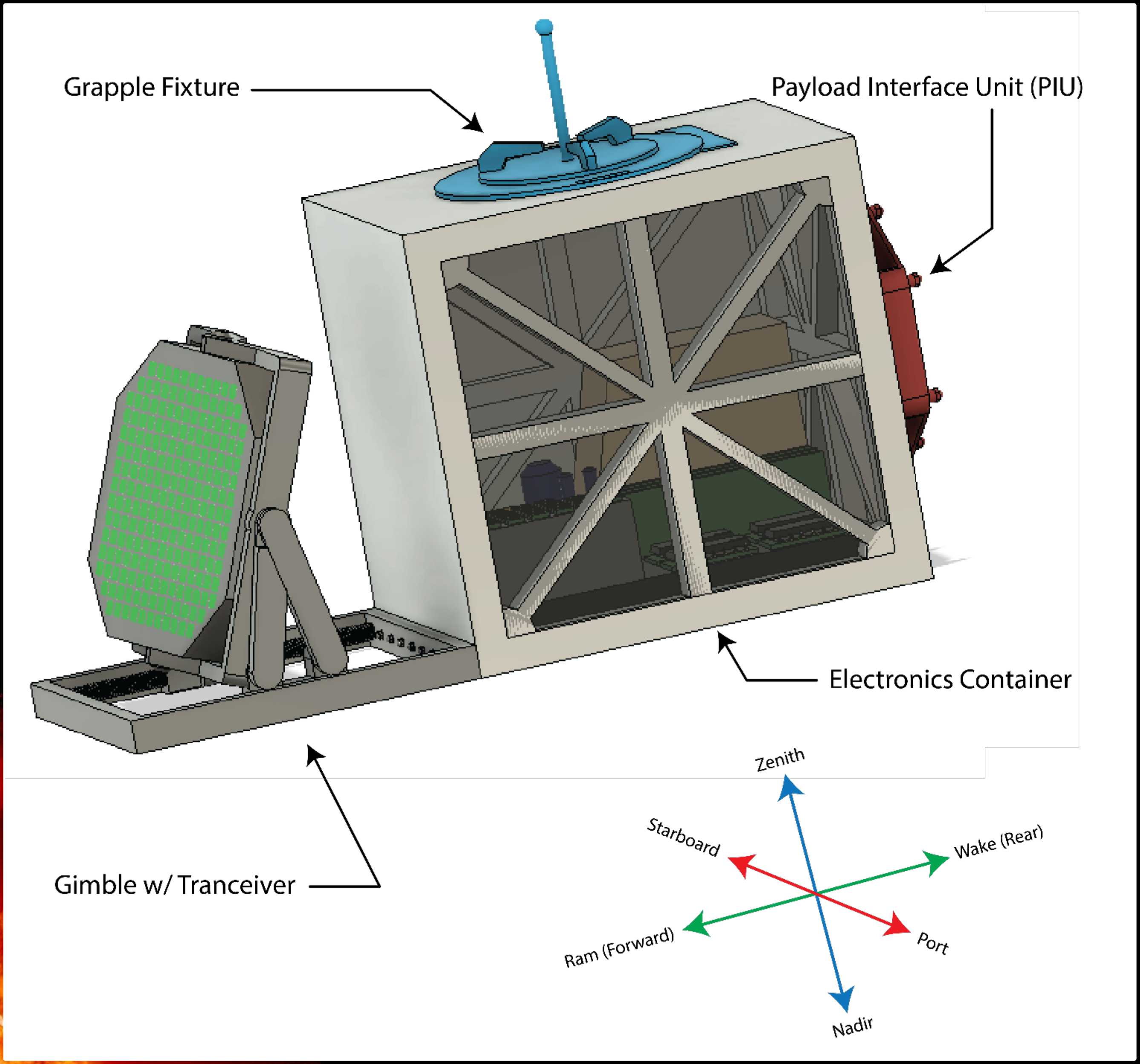

Communications
Receiving & Transmitting
Microwaves
Receiving Only (Power)
Visible Light
Receiving Only (Power)
Feed & Receiver
Layer 1 - Solar Panel
Layer 2 - Rectenna
Layer 3 - Communications Reflector
Reflecting Elements

SSPB ISS Transceiver Design Heritage

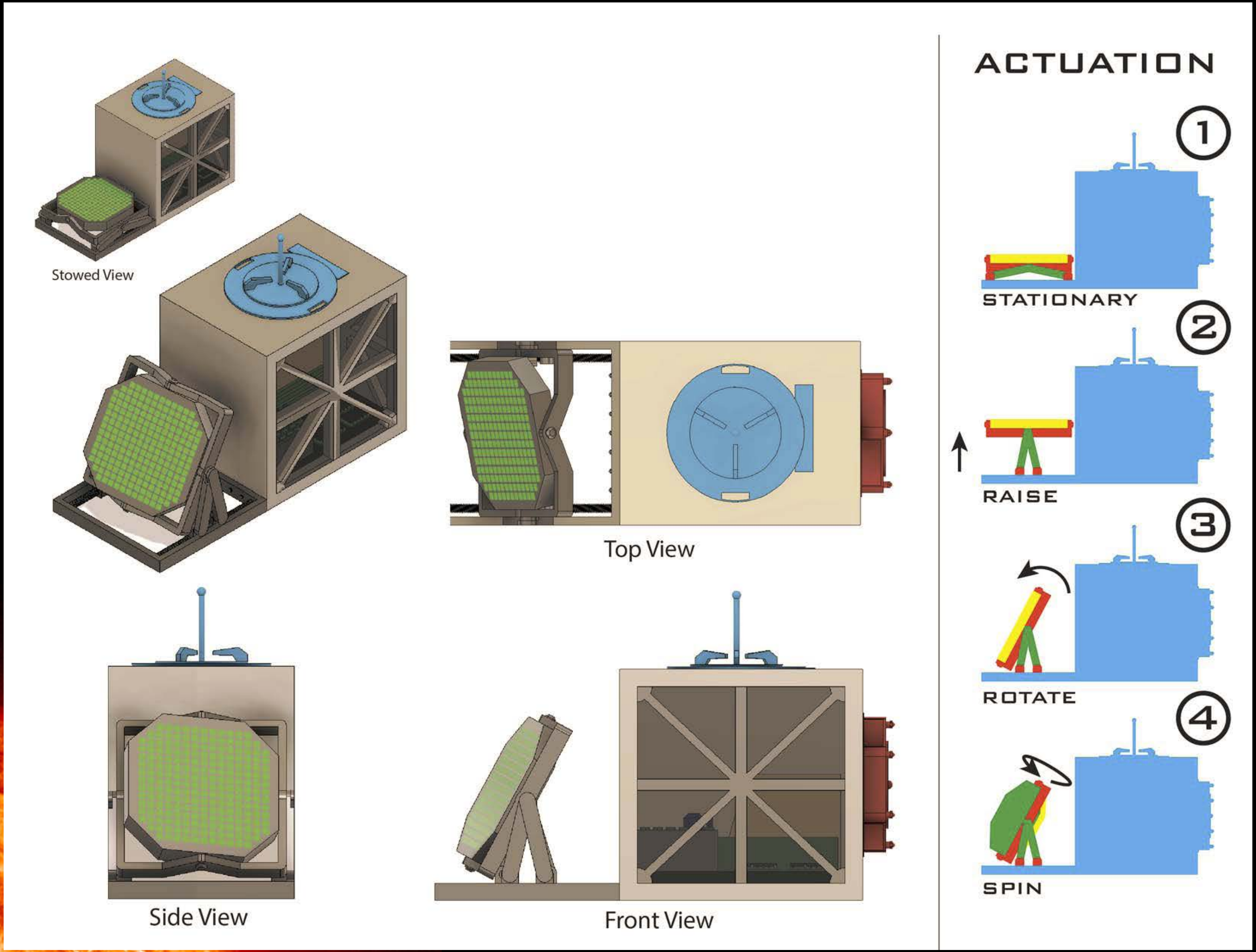
JAXA Inter-orbit
Comm System (ICS-EF)

Terrestrial 95 GHz Transmitter
(AFRL / Raytheon Design)

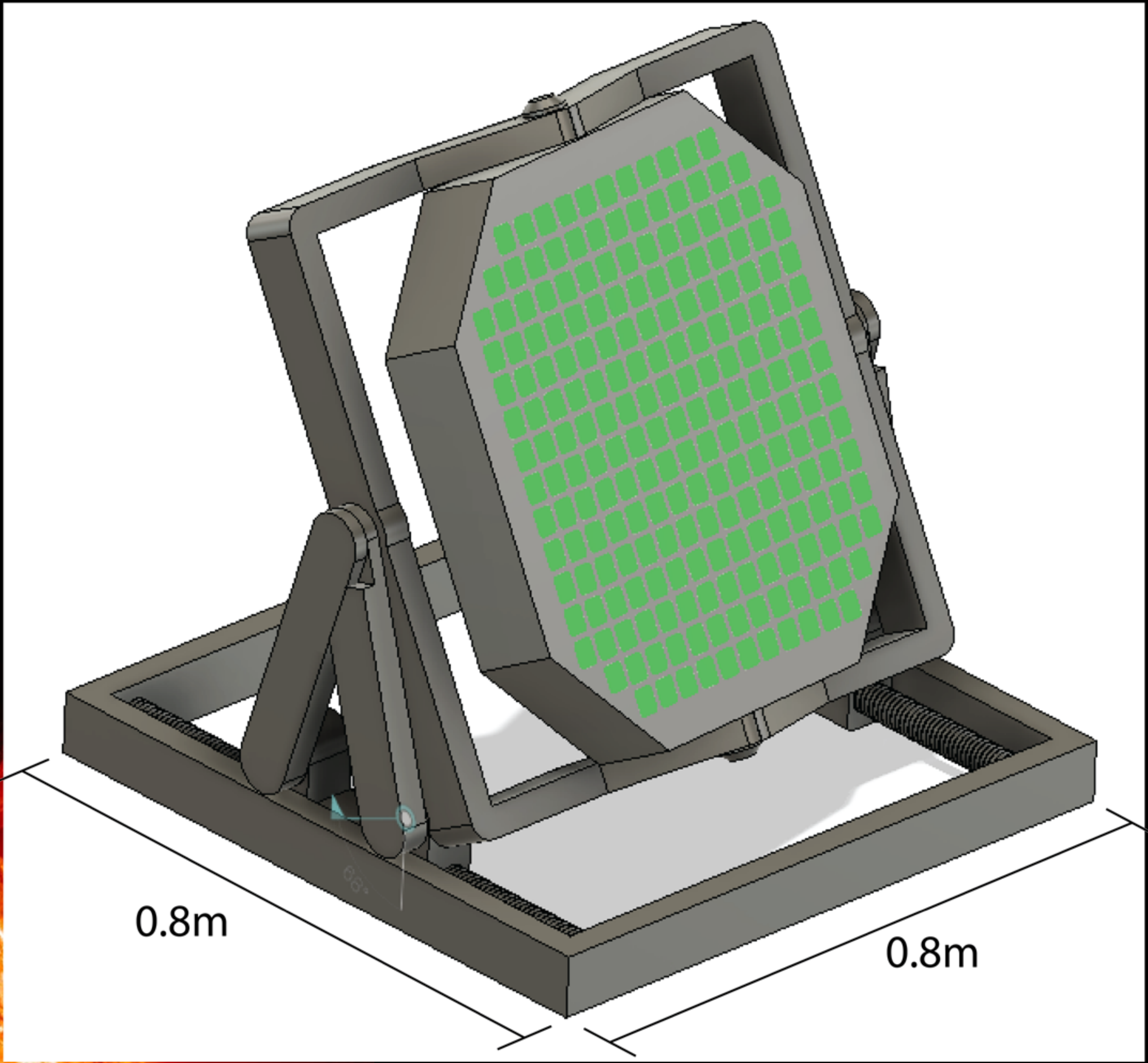
SSPB Transceiver Preliminary Design Isometric



SSPB Transceiver Preliminary Design Mechanicals

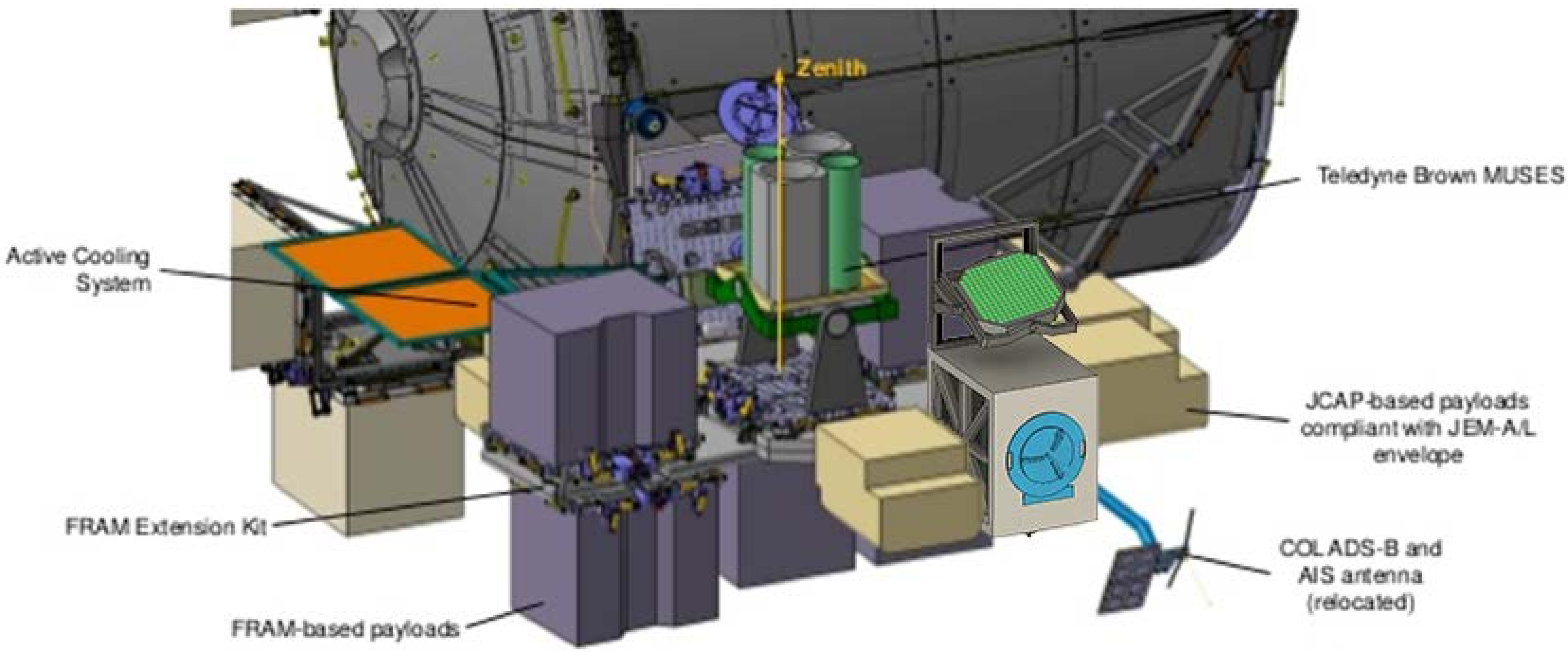


SSPB Transceiver Preliminary Design Phased Array



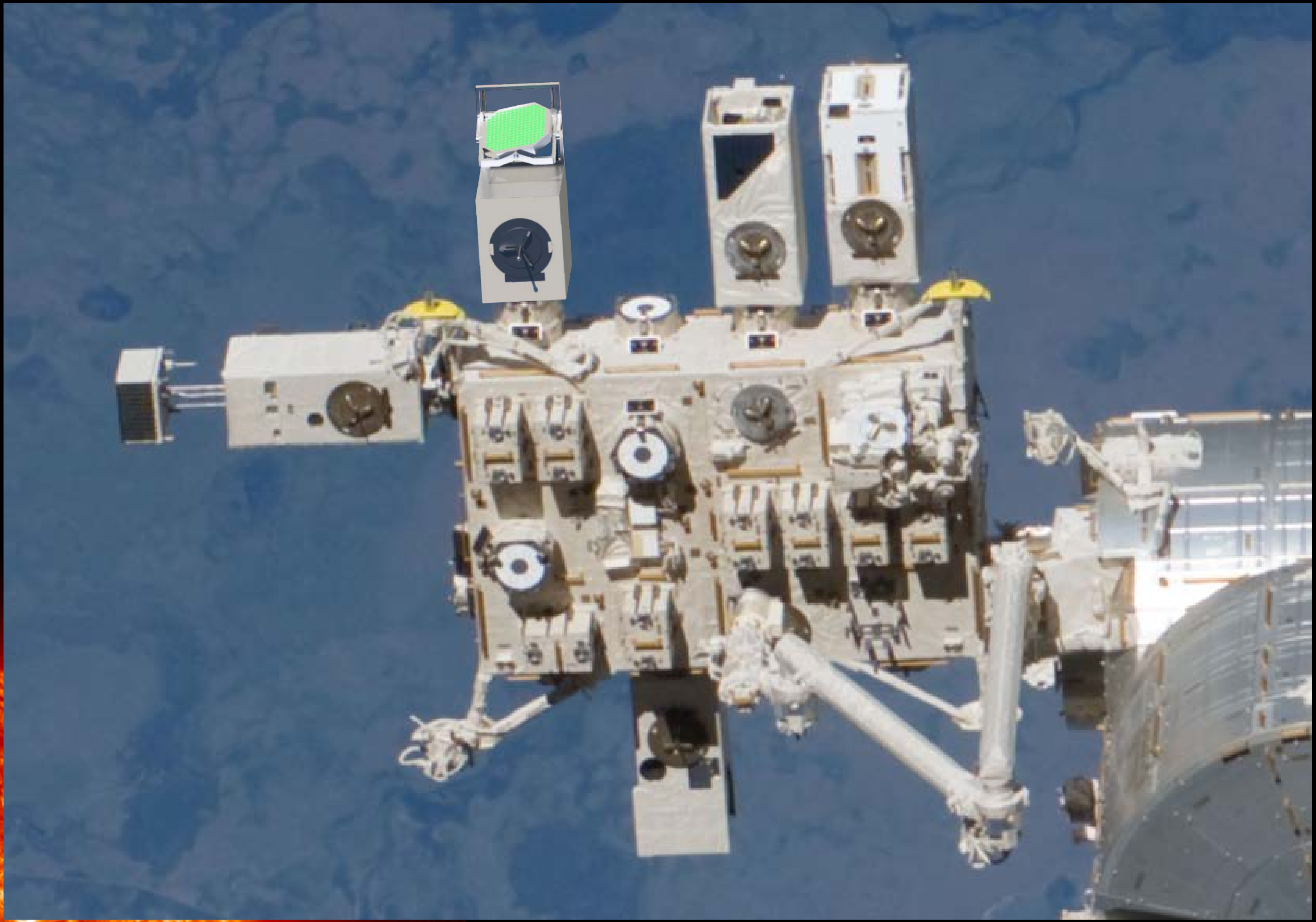
Barto Exposed Facility Accommodations

Bartolomeo On-orbit Configuration (3/4)



AIRBUS DEFENCE & SPACE

JEM Exposed Facility Accommodations



JEM & Bartolomeo Exposed Facility Accommodations

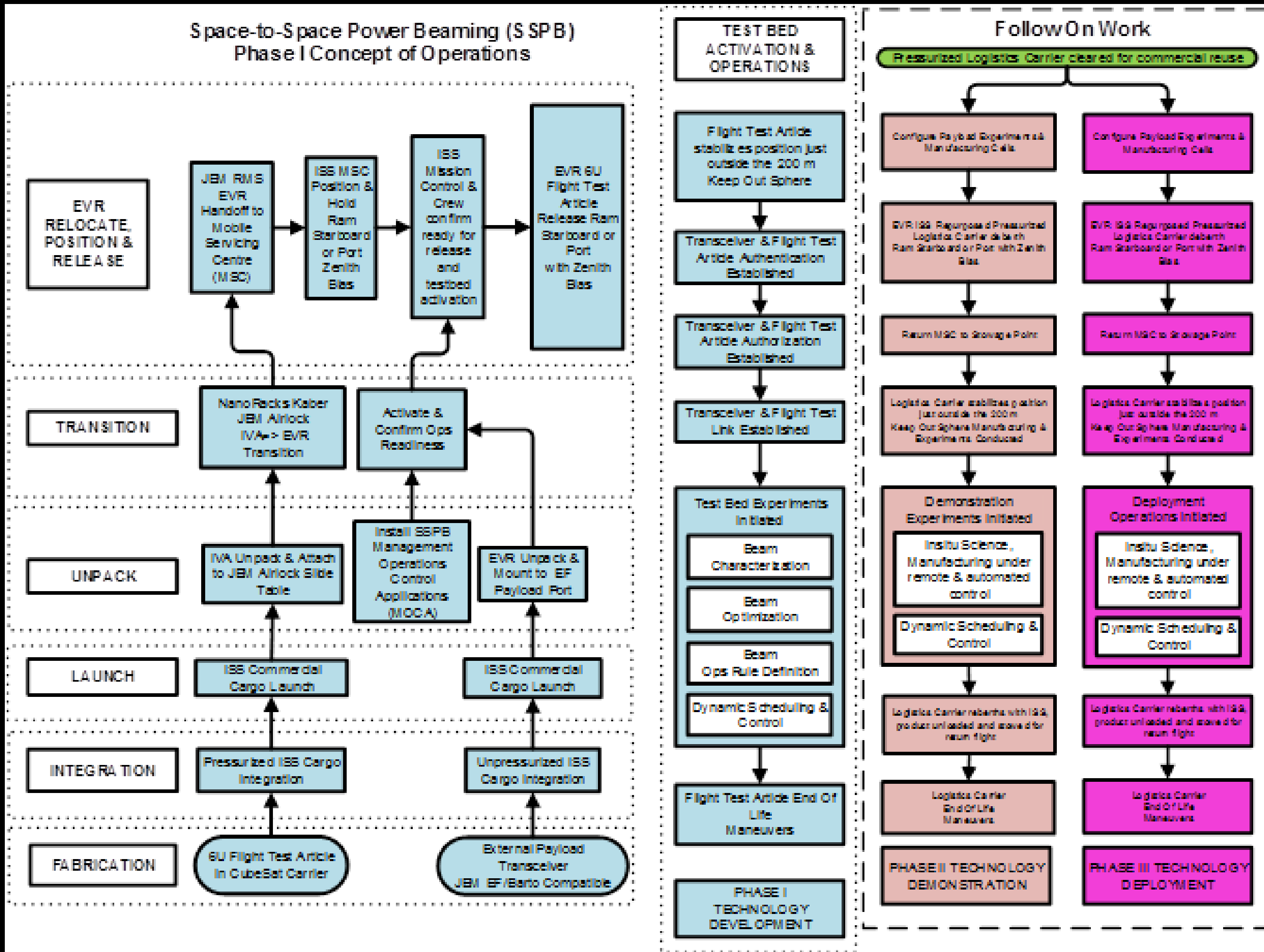
	ISS Transceiver	6U Flight Test Article	Cygnus
Payload Accommodation Type	Bartolomeo: Double Payload (Barto); Standard EF Payload (JEM EF)	Not Applicable	Not Applicable
Launch Type	Unpressurized Cargo	Pressurized or Unpressurized Cargo	Pressurized Logistics Carrier
Field of View	Ram and Zenith, gimballed 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	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)	Not Applicable	Not Applicable
	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)	Wireless: RF Link to SSPB ISS Transceiver, TBD Mbps max operations, TBD Mbps nominal operations, TBD kbps keep alive, TBD Mbps Downlink/Uplink nominal operations	Wireless: RF Link to SSPB ISS Transceiver, TBD Mbps max operations, TBD Mbps nominal operations, TBD kbps keep alive, TBD Mbps Downlink/Uplink nominal operations
Surface Area	less than 1 m^2 for transceiver	less than 1 m^2 for rectenna	less than 1 m^2 for rectenna
Payload return	Yes for one or more EVR compatible Orbital Replaceable Units, but not mandatory	No, unless retreival becomes an available option	No, unless retreival 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

Cygnus & Dragon Free flyers

THE VALUE OF PERFORMANCE.
NORTHROP GRUMMAN

SPACEX

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 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^3 Mission Set

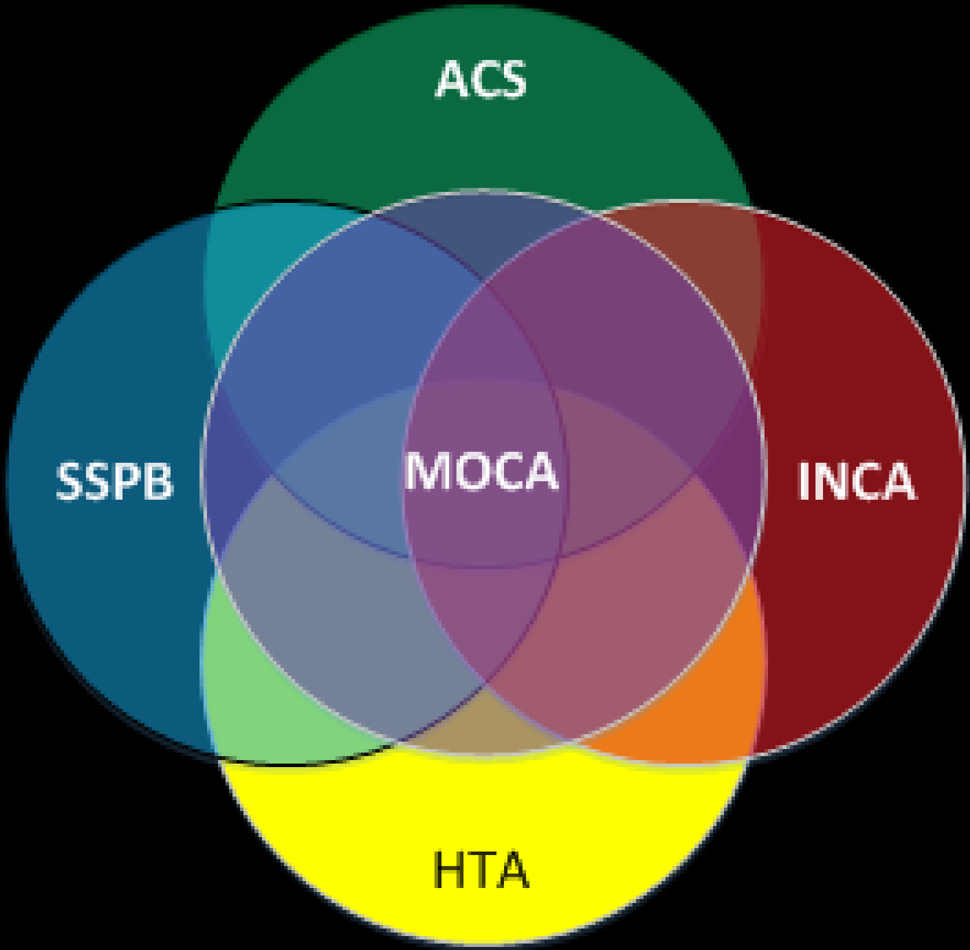
Alpha CubeSat (ACS)

Space-to-Space Power Beaming (SSPB)

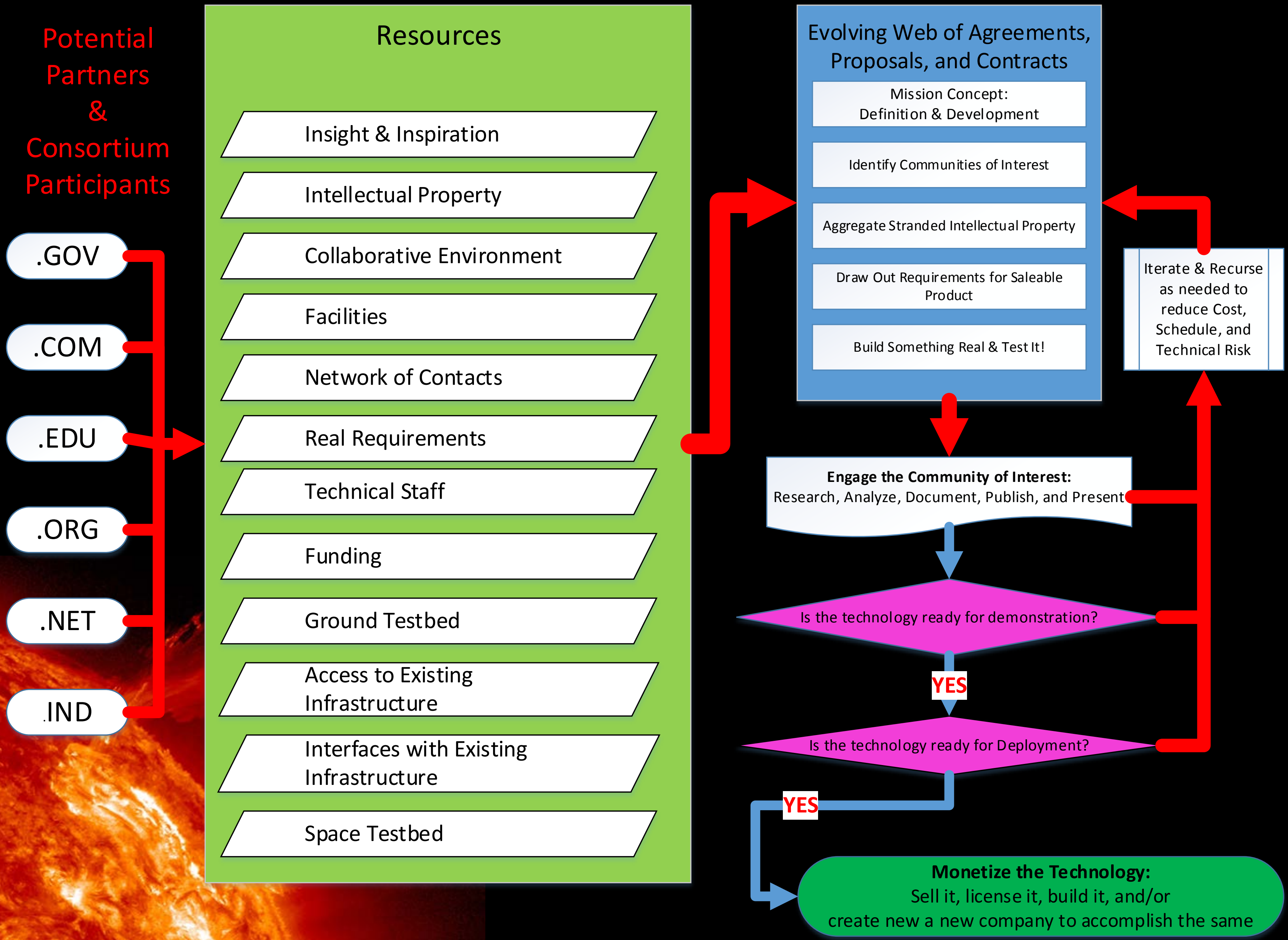
Halfway To Anywhere (HTA)

Interoperable Network Communication Architecture (INCA)

Mission Operations Control Applications (MOCA)

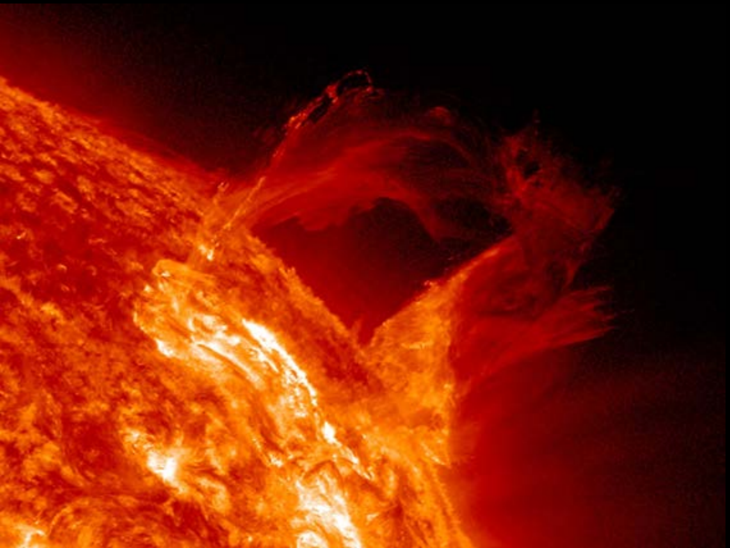


XISP-Inc "Follow the Resources" Mission Development Diagram



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



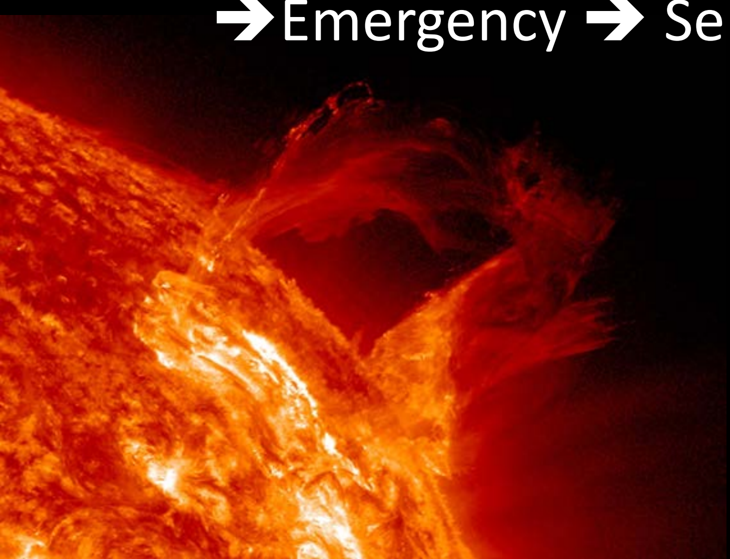
SSPB Phase II - Technology Deployment Components

- 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.



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 TD³ 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	2022	2025	2029	2038	2047
ISS TD³	LEO TD³	GEO TD³	GEO TD³	GEO TD³	SSP's >
3-6 KW	~100 KW	~100 MW	~2 GW	10 GW	50 GW
SSP Testbed	SSP LEO Demo	SSP GEO Demo	Full SSP		
NASA/DOD	NASA/DOD/DOE	NASA/DOD/DOE	Electrical Utility		
Commercial	Commercial	Commercial	Commercial		
Co-orbiting Test	ComSats Recovery	ComSats Primary	→ $$$	→ $$$$	
Platform Model	Platform TD³	Platform Ops	→ $$$	→ $$$$	
Spectrum Model	Spectrum Apply	Spectrum Allocation			
Orbit Slot Model	Orbit Slot Apply	Orbit Slot Allocation			
LP&L Seed/Angel	LP&L Series A/B/C	LP&L IPO	→ $$$	→ $$$$	
Co-orbiting Tests	Co-orbiting Labs	Co-orbiting Facilities	→ $$$	→ $$$$	
	Lunar Test(s)	Lunar Operations	→ $$$	→ $$$$	
	NEO Test(s)	Asteroidal Assay	→ $$$	→ $$$$	

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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.

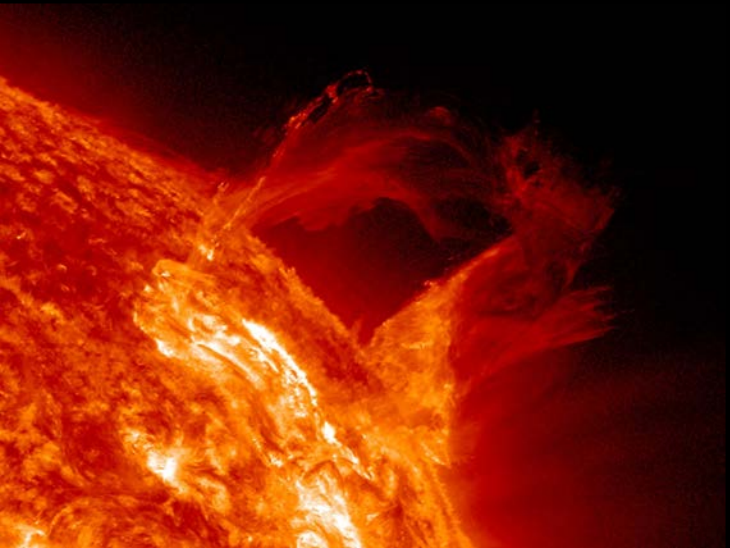
Theoretical Maximum Possible DC to DC Efficiency
Circa 1992 ~76%
Circa 2016 85-95%*** @ < 6 GHz and TBD @ Higher Frequencies
Experimental DC to DC Efficiency Circa 1992 ~54 %, Circa 2016 TBD but significantly higher

*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

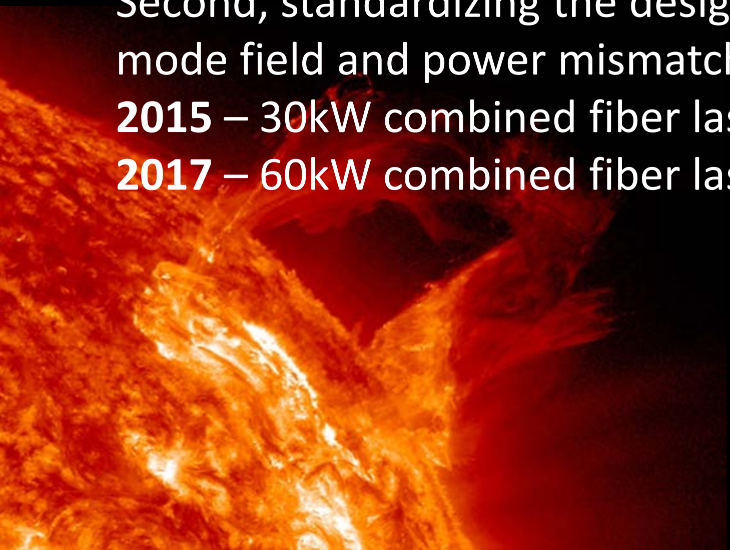
2013 – Propagation efficiencies of 90 percent, at a range of 1.2 kilometers (km), with transmitted continuous-wave power levels of 3 kilowatt (kW) – U.S. Naval Research Laboratory

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

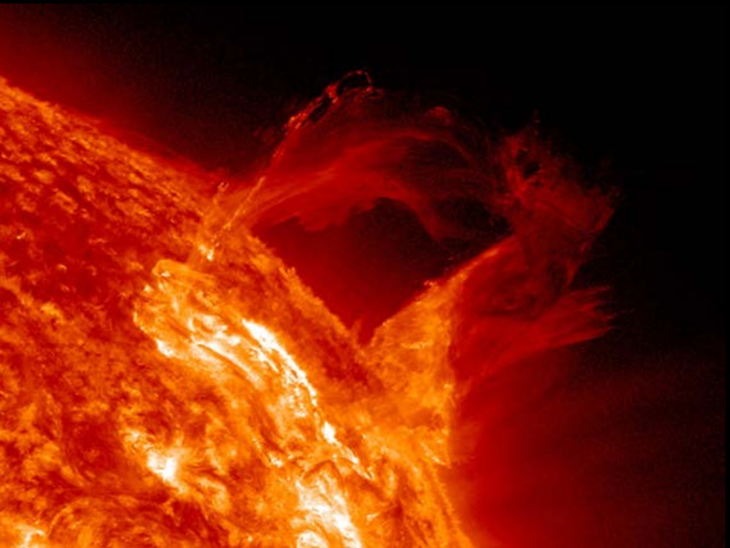


Demonstrated source power to beam efficiency of 43 percent

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

λ^2 is the wavelength squared

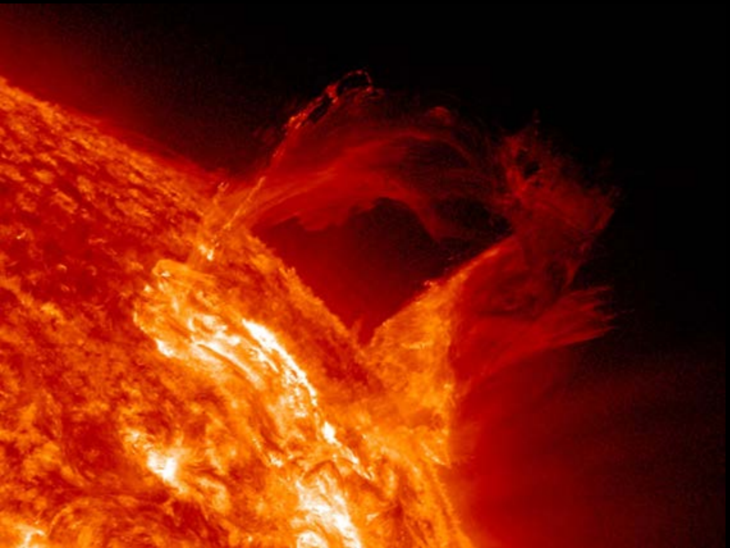
D^2 is the separation between the apertures squared

*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 (Pr) calculations break down using the far-field equations.

Accordingly, the Pr 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

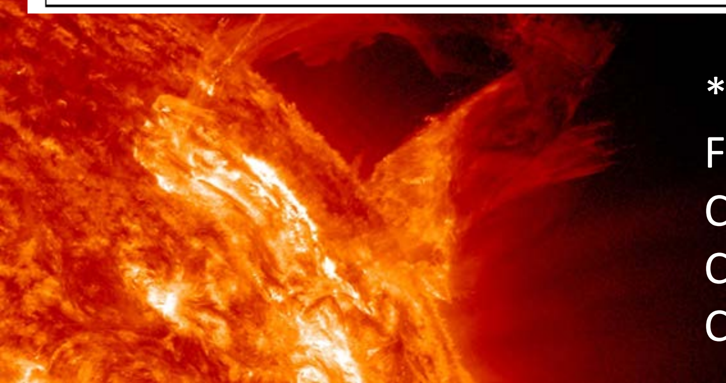
Power Density* - More Optimal Solutions

CASE 1 - Space Station Ka Band Transmitter Anticipated Power Received for various rectenna areas - Ka Low 26.5 GHz						
Distance (meters)	Rectenna Area (cm^2)	Wavelength (cm)	Transmitter Area (cm^2)	Power Transmitted (Watts)	Power Density (Watts/cm^2)	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^2)	Wavelength (cm)	Transmitter Area (cm^2)	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^2)	Wavelength (cm)	Transmitter Area (cm^2)	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_t= 3000 W and A_t = 10000 cm^2



*Power Received with P_t = 3000 W and A_t = 10000 cm^2

For rectennas ranging from 100 cm^2 to 10000 cm^2

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

Distance (meters)	Rectenna Area (cm^2)	Wavelength (cm)	Transmitter Area (cm^2)	Power Transmitted (Watts)	Power Density (Watts/cm^2)	Power Received (Watts)
D	Ar	λ	At	Pt	Pd	Pr
200	**100**	1.13	10000	6000	0.117472	**11.70**
200	**200**	1.13	10000	6000	0.117472	**23.24**
200	**300**	1.13	10000	6000	0.117472	**35.32**
200	**400**	1.13	10000	6000	0.117472	**46.57**
200	**500**	1.13	10000	6000	0.117472	**57.54**
200	**600**	1.13	10000	6000	0.117472	**71.76**
200	**700**	1.13	10000	6000	0.117472	**81.33**
200	**800**	1.13	10000	6000	0.117472	**96.12**
200	**900**	1.13	10000	6000	0.117472	**103.56**
200	**1000**	1.13	10000	6000	0.117472	**114.78**
200	**2000**	1.13	10000	6000	0.117472	**230.50**
200	**3000**	1.13	10000	6000	0.117472	**340.86**
200	**4000**	1.13	10000	6000	0.117472	**452.33**
200	**5000**	1.13	10000	6000	0.117472	**557.78**
200	**6000**	1.13	10000	6000	0.117472	**662.30**
200	**7000**	1.13	10000	6000	0.117472	**767.38**
200	**8000**	1.13	10000	6000	0.117472	**869.41**
200	**9000**	1.13	10000	6000	0.117472	**964.66**
200	**10000**	1.13	10000	6000	0.117472	**1064.30**

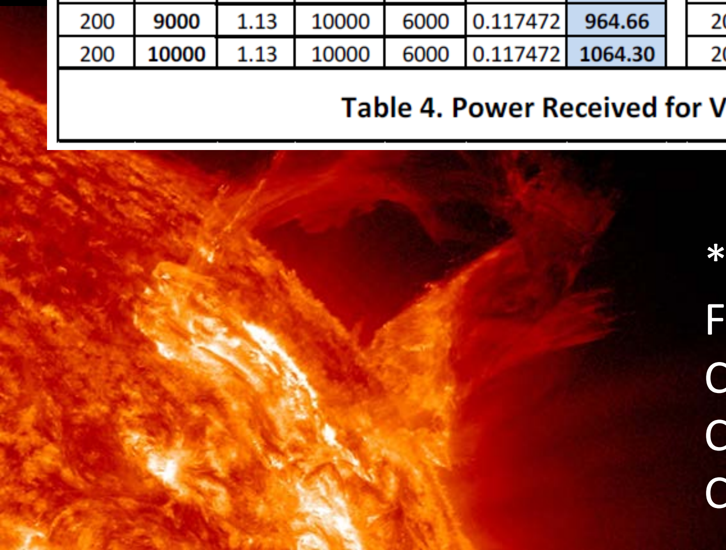
CASE 2 - Space Station Ka Band Transmitter Anticipated Power Received for various rectenna areas - Ka 36 GHz

Distance (meters)	Rectenna Area (cm^2)	Wavelength (cm)	Transmitter Area (cm^2)	Power Transmitted (Watts)	Power Density (watts/cm**2)	Power Received (Watts)
D	Ar	λ	At	Pt	Pd	Pr
200	**100**	0.833	10000	6000	0.216173	**21.65**
200	**200**	0.833	10000	6000	0.216173	**42.92**
200	**300**	0.833	10000	6000	0.216173	**63.62**
200	**400**	0.833	10000	6000	0.216173	**85.53**
200	**500**	0.833	10000	6000	0.216173	**105.38**
200	**600**	0.833	10000	6000	0.216173	**130.73**
200	**700**	0.833	10000	6000	0.216173	**148.73**
200	**800**	0.833	10000	6000	0.216173	**172.67**
200	**900**	0.833	10000	6000	0.216173	**193.44**
200	**1000**	0.833	10000	6000	0.216173	**214.71**
200	**2000**	0.833	10000	6000	0.216173	**418.24**
200	**3000**	0.833	10000	6000	0.216173	**614.71**
200	**4000**	0.833	10000	6000	0.216173	**804.84**
200	**5000**	0.833	10000	6000	0.216173	**987.65**
200	**6000**	0.833	10000	6000	0.216173	**1163.68**
200	**7000**	0.833	10000	6000	0.216173	**1335.76**
200	**8000**	0.833	10000	6000	0.216173	**1499.85**
200	**9000**	0.833	10000	6000	0.216173	**1659.73**
200	**10000**	0.833	10000	6000	0.216173	**1808.88**

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

Distance (meters)	Rectenna Area (cm^2)	Wavelength (cm)	Transmitter Area (cm^2)	Power Transmitted (Watts)	Power Density (watts/cm**2)	Power Received (Watts)
D	Ar	λ	At	Pt	Pd	Pr
200	**100**	0.316	10000	6000	1.502163	**147.83**
200	**200**	0.316	10000	6000	1.502163	**291.94**
200	**300**	0.316	10000	6000	1.502163	**435.64**
200	**400**	0.316	10000	6000	1.502163	**574.41**
200	**500**	0.316	10000	6000	1.502163	**709.18**
200	**600**	0.316	10000	6000	1.502163	**837.94**
200	**700**	0.316	10000	6000	1.502163	**964.26**
200	**800**	0.316	10000	6000	1.502163	**1093.18**
200	**900**	0.316	10000	6000	1.502163	**1214.43**
200	**1000**	0.316	10000	6000	1.502163	**1329.54**
200	**2000**	0.316	10000	6000	1.502163	**2352.57**
200	**3000**	0.316	10000	6000	1.502163	**3124.48**
200	**4000**	0.316	10000	6000	1.502163	**3700.93**
200	**5000**	0.316	10000	6000	1.502163	**4129.07**
200	**6000**	0.316	10000	6000	1.502163	**4441.50**
200	**7000**	0.316	10000	6000	1.502163	**4659.60**
200	**8000**	0.316	10000	6000	1.502163	**4800.55**
200	**9000**	0.316	10000	6000	1.502163	**4897.40**
200	**10000**	0.316	10000	6000	1.502163	**4963.66**

Table 4. Power Received for Various Rectenna Sizes with D=200 m, P_t= 6000 W and A_t = 10000 cm^2



*Power Received with P_t = 6000 W and A_t = 10000 cm^2

For rectennas ranging from 100 cm^2 to 10000 cm^2

Case 1 frequency = 26.5 GHz ➔ λ = 1.13 cm

Case 2 frequency = 36.0 GHz ➔ λ = .833 cm

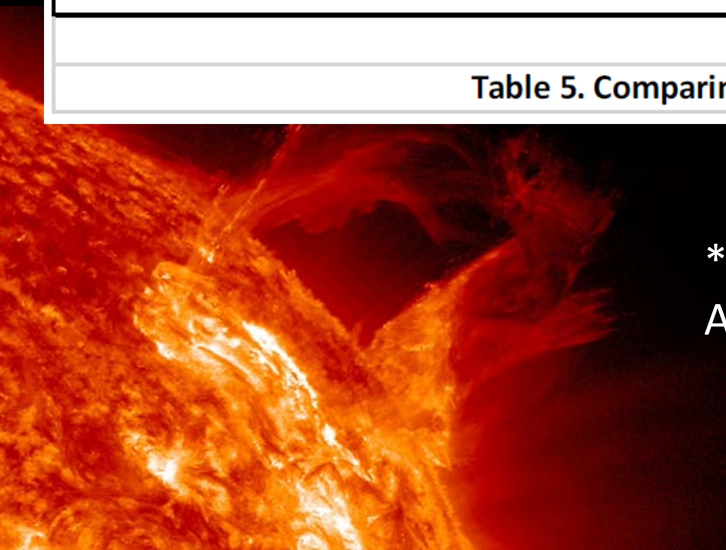
Case 3 frequency = 95.0 GHz ➔ λ = 0.316 cm

Power Density* versus the Solar Constant

	Power Density (Watts/cm²) P_d Case 1 @26.5 GHz	Power Density (Watts/cm²) P_d Case 2 @36 GHz	Power Density (Watts/cm²) P_d Case 3 @95 GHz
Table 1. Power Density with D=200 m, P_t= 3000 W and A_t = 1642 cm^2	0.00964	0.01774	0.12331
Table 2. Power Density with D=200 m, P_t= 6000 W and A_t = 1642 cm^2	0.01929	0.03549	0.24661
Table 3. Power Density with D=200 m, P_t= 3000 W and A_t = 10000 cm^2	0.05874	0.10809	0.75108
Table 4. Power Density with D=200 m, P_t= 6000 W and A_t = 10000 cm^2	0.11747	0.21617	1.50216

I_{sc} = Solar Constant at 1 AU = 0.1367 Watts/cm2	P_d significantly lower than I_{sc}
	P_d similar to I_{sc}
	P_d significantly higher than I_{sc}

Table 5. Comparing Beaming Power Density and the Solar Constant



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

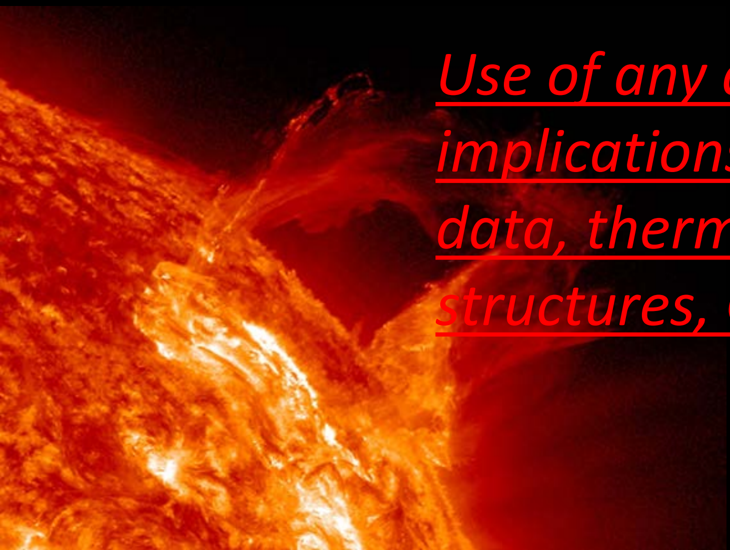
Technological Challenges

- 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

- GeoPolictical

– 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.

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!