Space Power & Ancillary Services Beaming: Creating Enabling Infrastructure

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Space Power Beaming & Ancillary Services

(1) Key Considerations
(2) Key Variables
(3) The Challenge Matrix
- The Problem/Trade Space
  - Ground & Space Technology Development
- Solution Space
  - Demonstration
  - Deployment

(4) Visualization
(5) XISP-Inc Space-to-Space Power Beaming Evolution
(6) Mission Technology, Development, and Demonstration TD^3

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

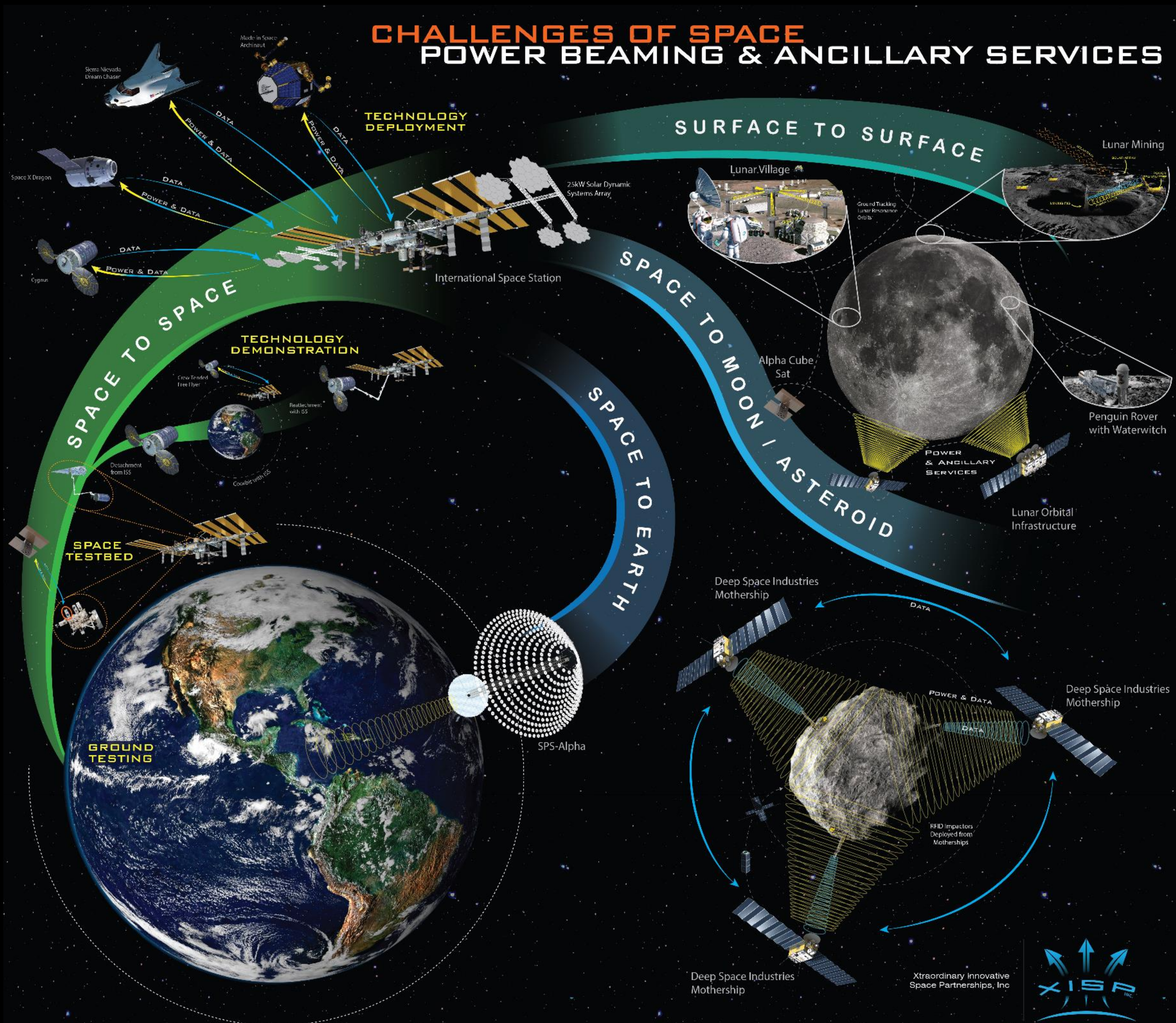
Space Solar Power Key Variables

- 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).

Work Vectors

Venues

	Space Solar Power Problem Space		Space Solar Power Solution Space	
	Technology Development		Operational Capability/Applications	
	Ground	Space	Technology Demonstration	Technology Deployment
Space - to - Space	• Cognitive SDR Transceiver • Converged Electro/Optics • W Band & Optical Apertures • Piecewise Efficiency • Reflectarray Rectenna • Beam Forming • Management Operations Control Applications (MOCA)	• 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	• 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 Interface Kit(s) • Dispatchable Power & Ancillary Services • Cislunar Propulsion Services • Kilowatt scale services
Surface - to - Surface	• Deployable Power Generation & Relay Towers • Conformal Rectenna • Deployable Rectenna • Solar Concentrator/Reflector	• Powered Rover • Powered Prospector • Powered Miner • Volatile/Metal Separation	• Power & Ancillary Services Beaming - Survive the Night • Volatiles Mining Demo • Propellant Depot Demo • Metals Mining Demo	• Dispatchable Power & Ancillary Services • 24x7 Operations Support • Kilowatt to Megawatt Scale Services
Space - to - Moon / Asteroid	• 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)	• 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	• Synergistic impact of Cislunar Development • Dispatchable Power & Ancillary Services • 24x7 Operations Support • Megawatt to Gigawatt Scale Services
Space - to - Earth	• 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	• Power & Ancillary Services Beaming to UAVs & Others • Power & Ancillary Services Beaming to Forward Bases • Power & Ancillary Services Beaming to Terrestrial Grid	• 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
Sierra Nevada Dream Chaser
Made in Space Archinaut
Space X Dragon
Cygnus
DATA
POWER & DATA
TECHNOLOGY DEPLOYMENT
25kW Solar Dynamic Systems Array
International Space Station
SURFACE TO SURFACE
Lunar Village
Lunar Mining
SPACE TO SPACE
TECHNOLOGY DEMONSTRATION
SPACE TO MOON / ASTEROID
Alpha Cube Sat
Penguin Rover with Waterwitch
POWER & ANCILLARY SERVICES
Lunar Orbital Infrastructure
SPACE TO EARTH
SPACE TESTBED
GROUND TESTING
SPS-Alpha
Deep Space Industries Mothership
Deep Space Industries Mothership
Deep Space Industries Mothership
RFID Impactors Deployed from Motherships
Xtraordinary Innovative Space Partnerships, Inc
XISP

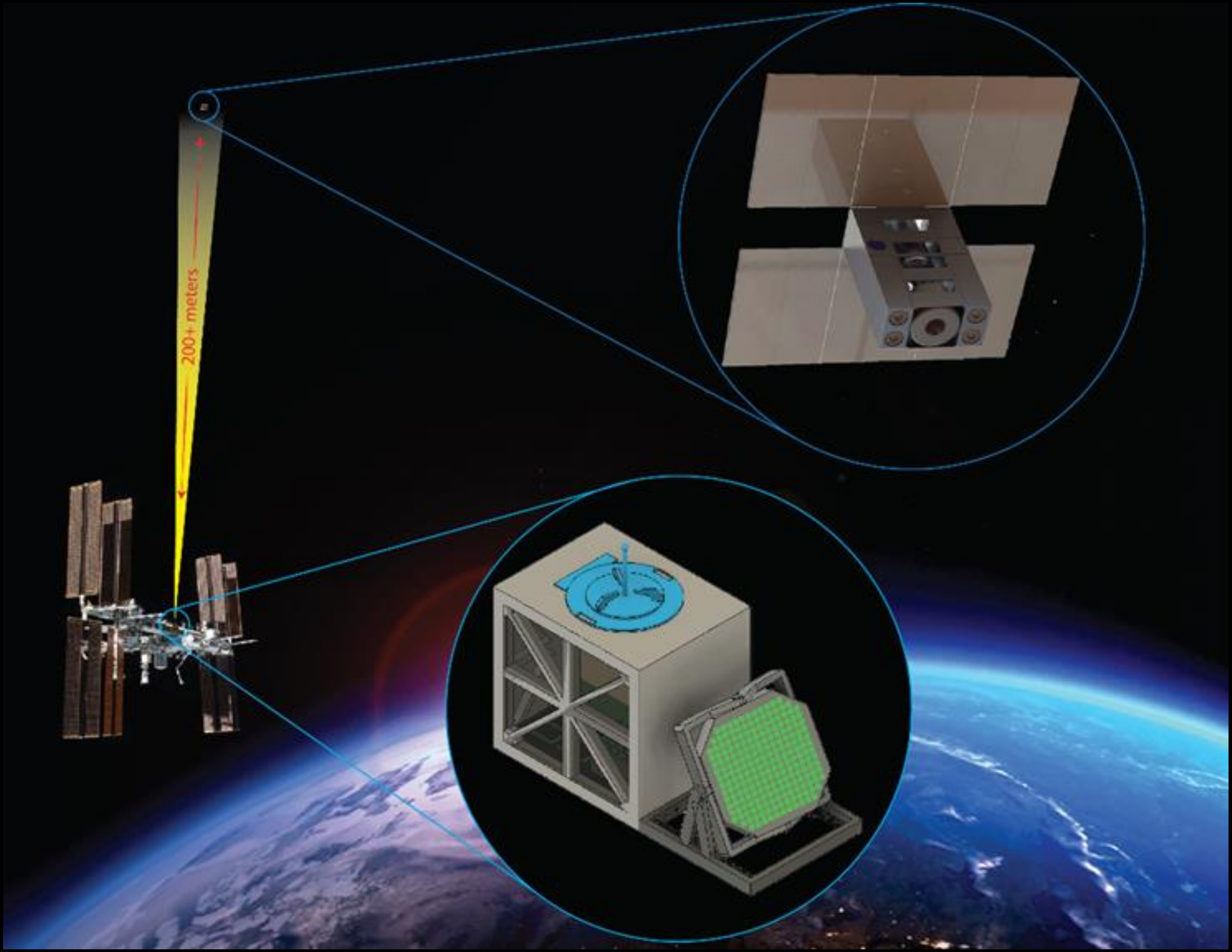
Space-to-Space Power Beaming (SSPB)

Technology Development, Demonstration, and Deployment (TD^3) Mission

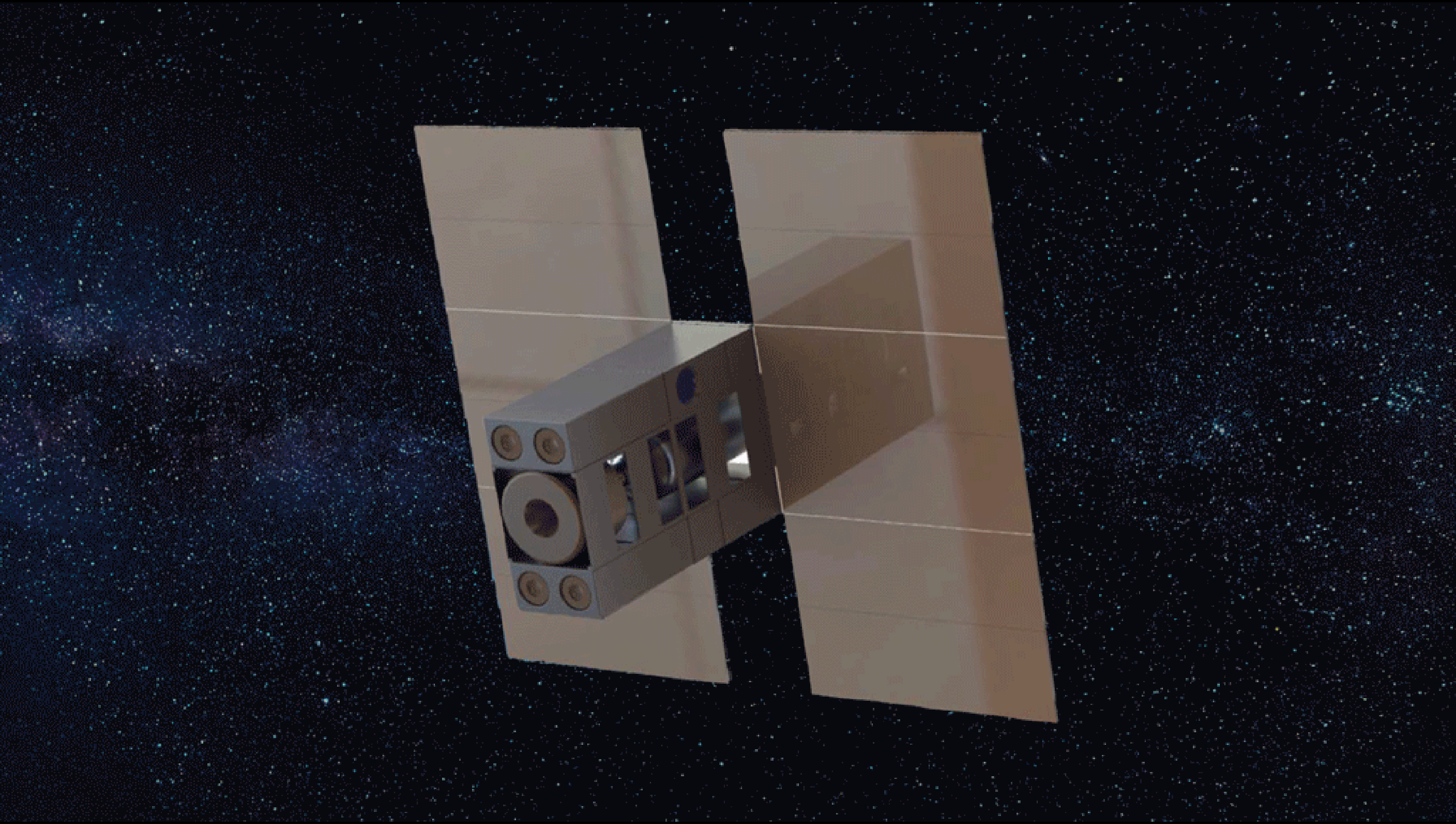
XISP-Inc has hypothesized that unbundling/disaggregating power systems (i.e. the separation of power generation, transmission, control, storage, and loads) can:

- 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)

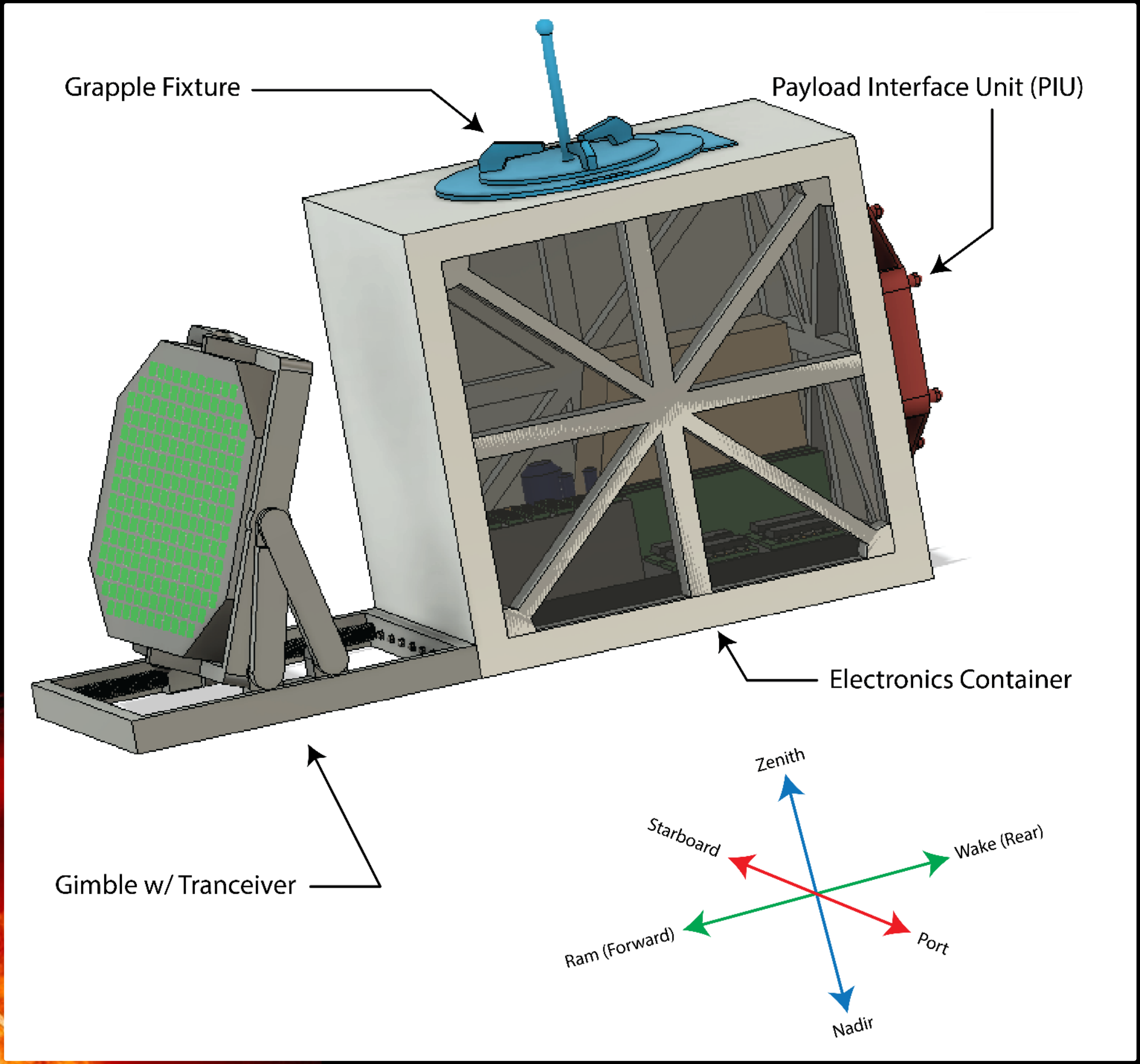
SSPB Mission Overview



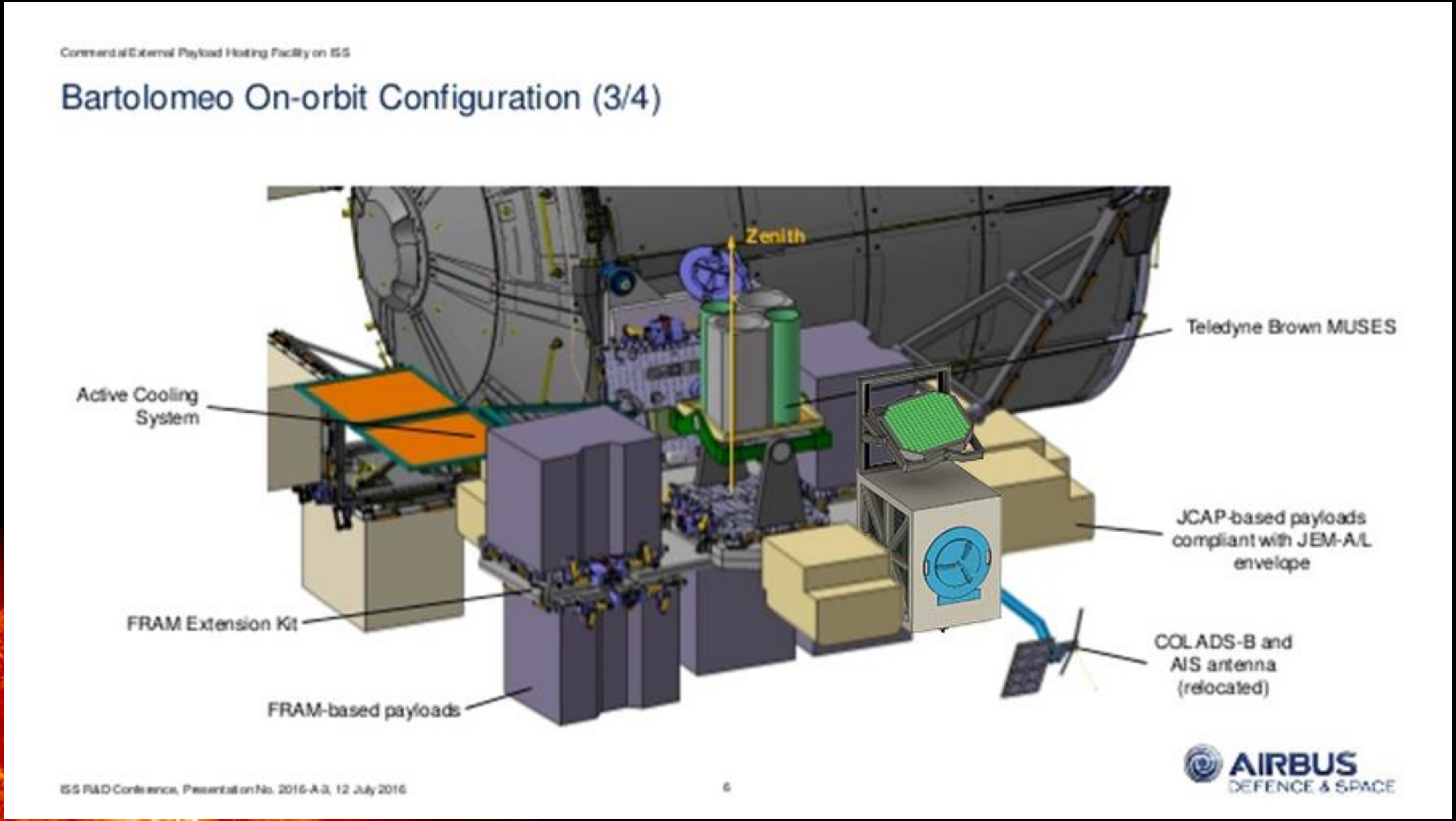
SSPB Mission Overview



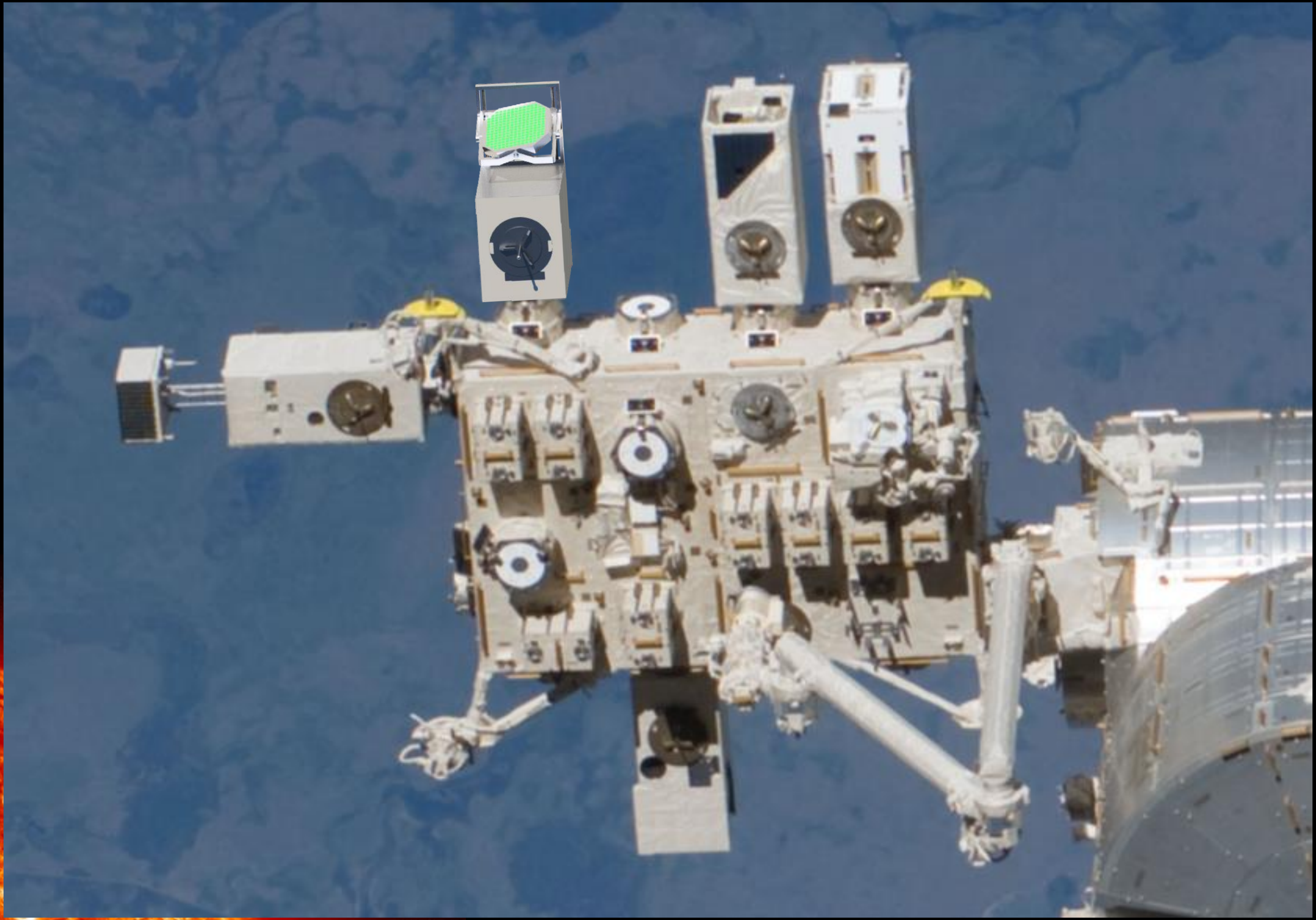
SSPB Transceiver Preliminary Design Isometric



Barto Exposed Facility Accommodations



JEM Exposed Facility Accommodations

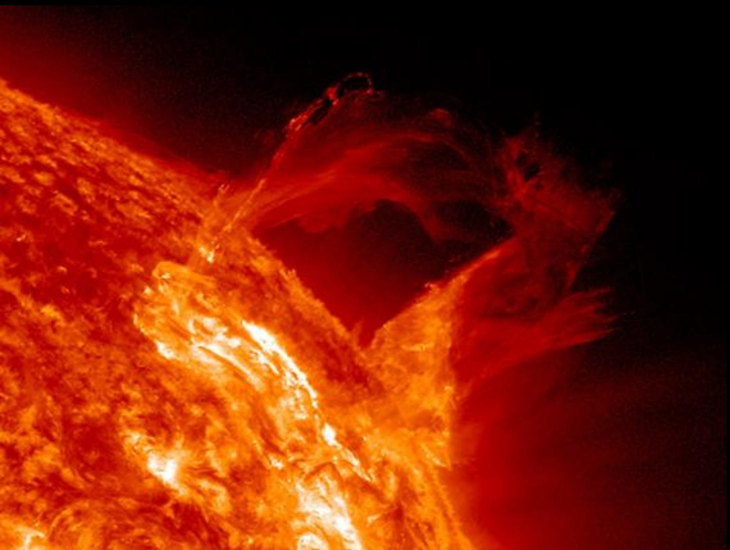


SSPB - Mission Overview

- 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^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 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



Cygnus & Dragon Free flyers

THE VALUE OF PERFORMANCE.
NORTHROP GRUMMAN

SPACEX

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.

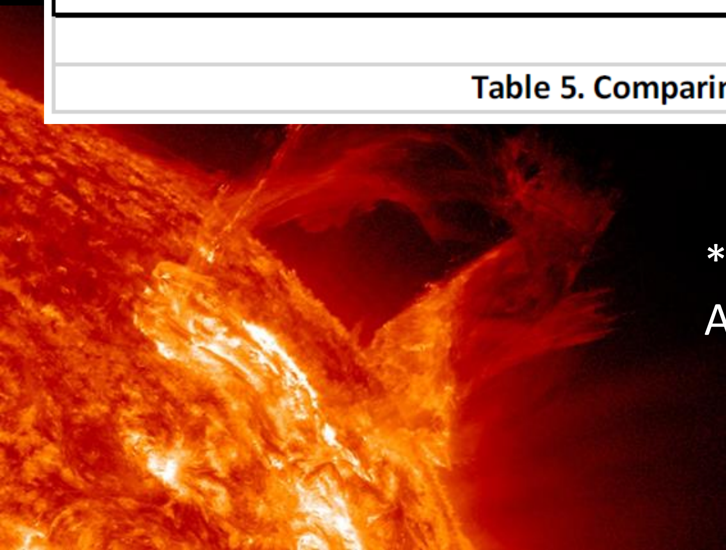
Power Density* versus the Solar Constant

	Power Density (Watts/cm^2) P_d Case 1 @26.5 GHz	Power Density (Watts/cm^2) P_d Case 2 @36 GHz	Power Density (Watts/cm^2) 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

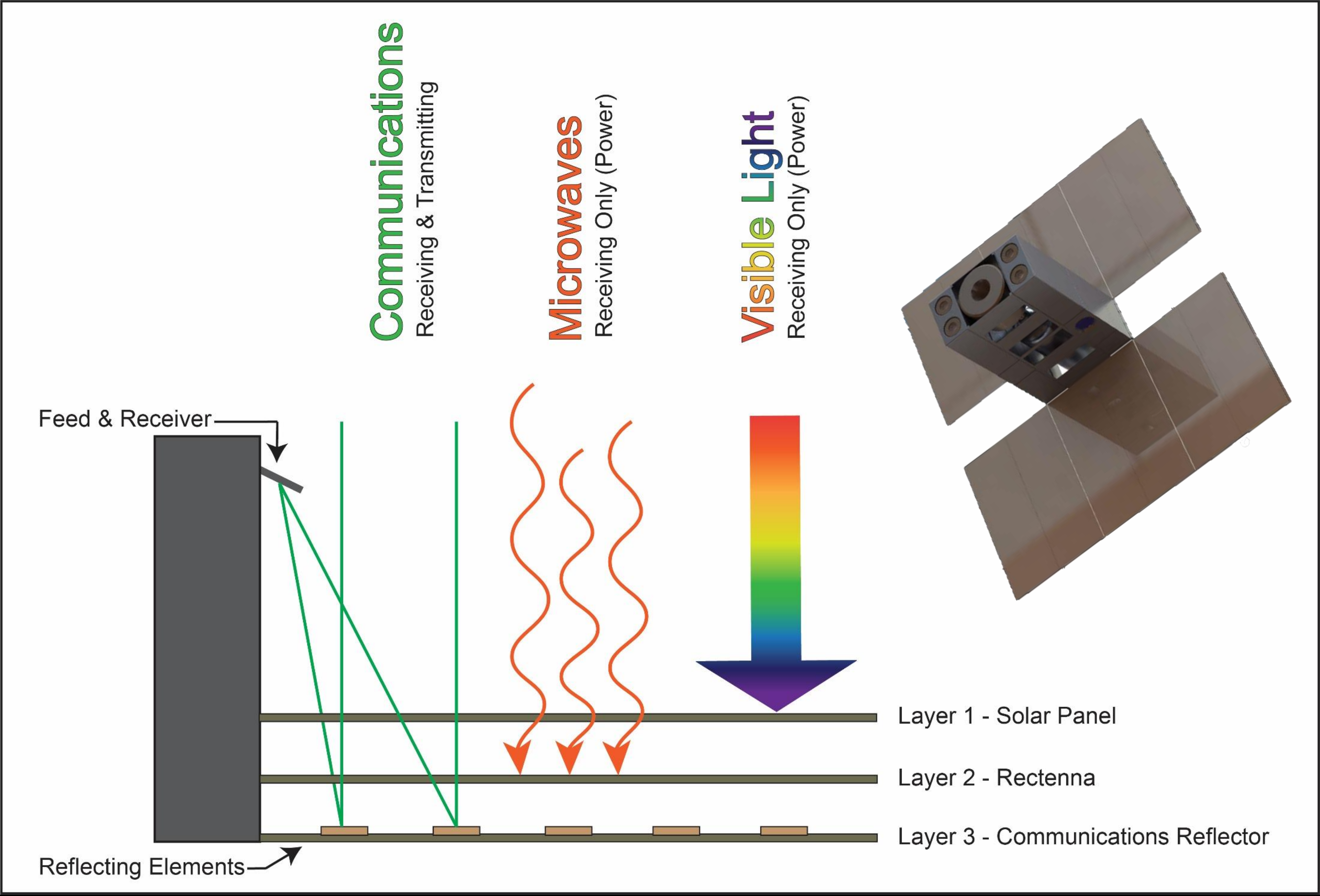
$$I_{sc} = Solar\ Constant\ at\ 1\ AU = 0.1367\ Watts/cm2$$

- P_d significantly lower than I_{sc}
- P_d similar to I_{sc}
- P_d significantly higher than I_{sc}

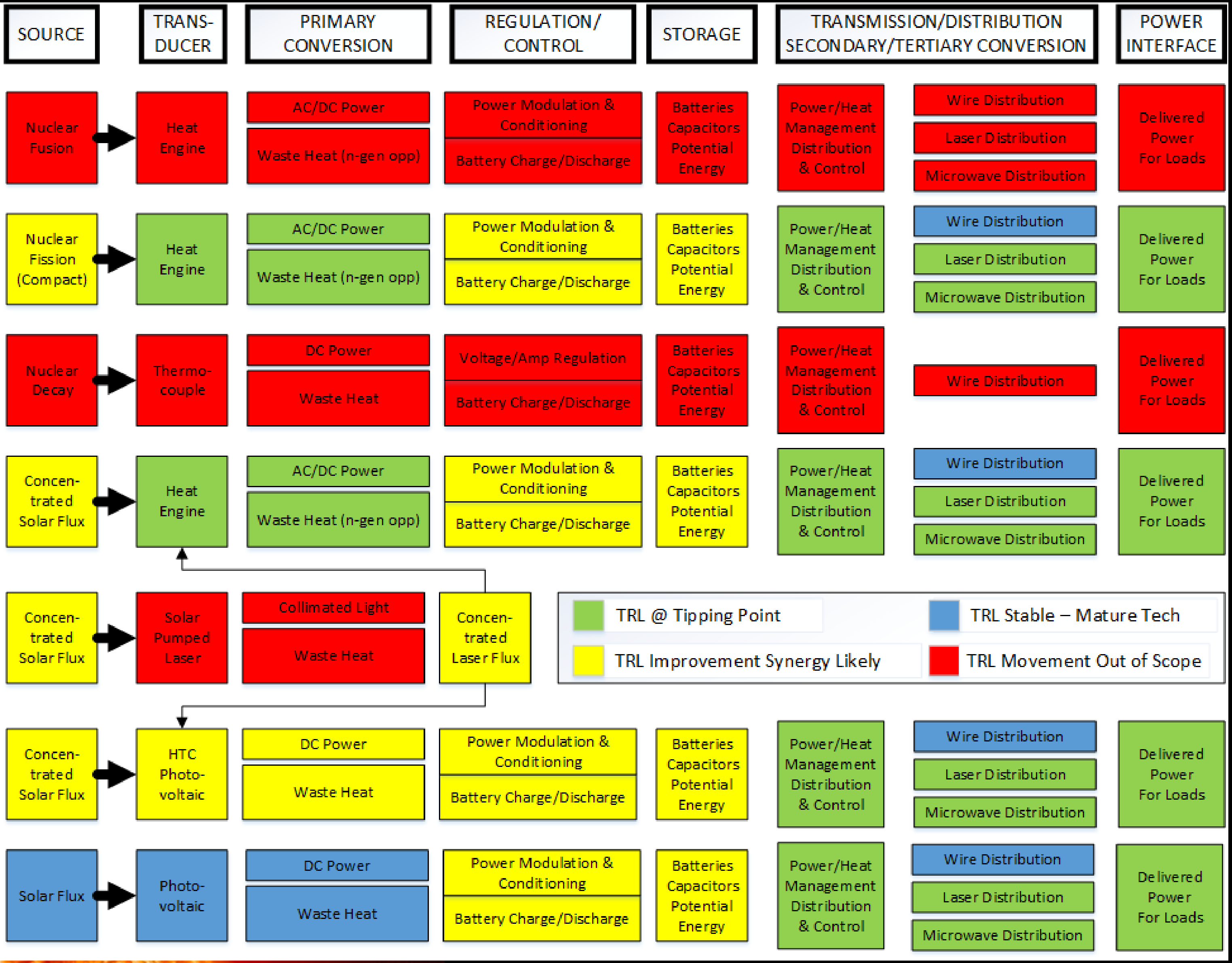
Table 5. Comparing Beaming Power Density and the Solar Constant



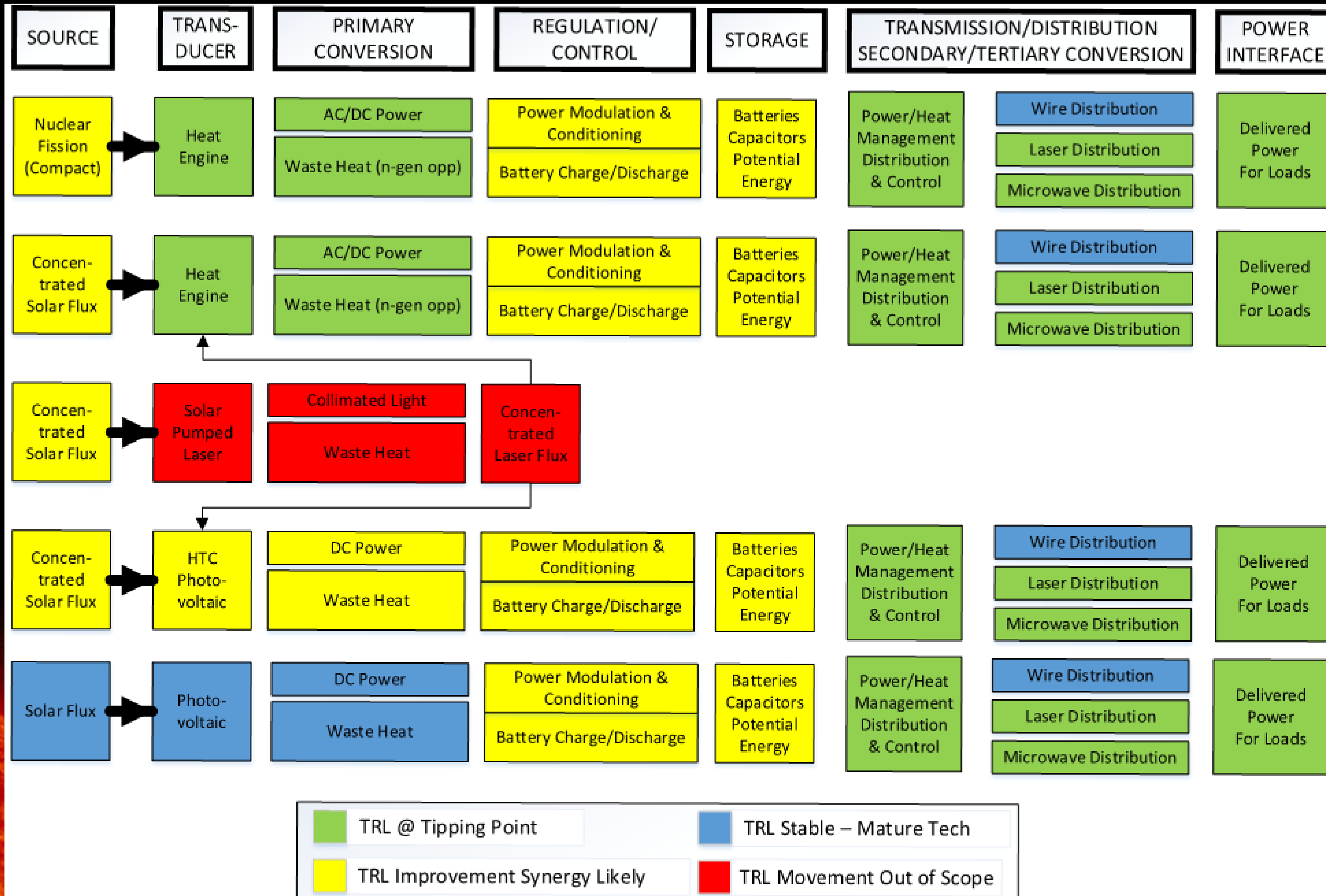
*Barnhard, Gary Pearce Space-to Space Power Beaming AIAA Space 2017


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

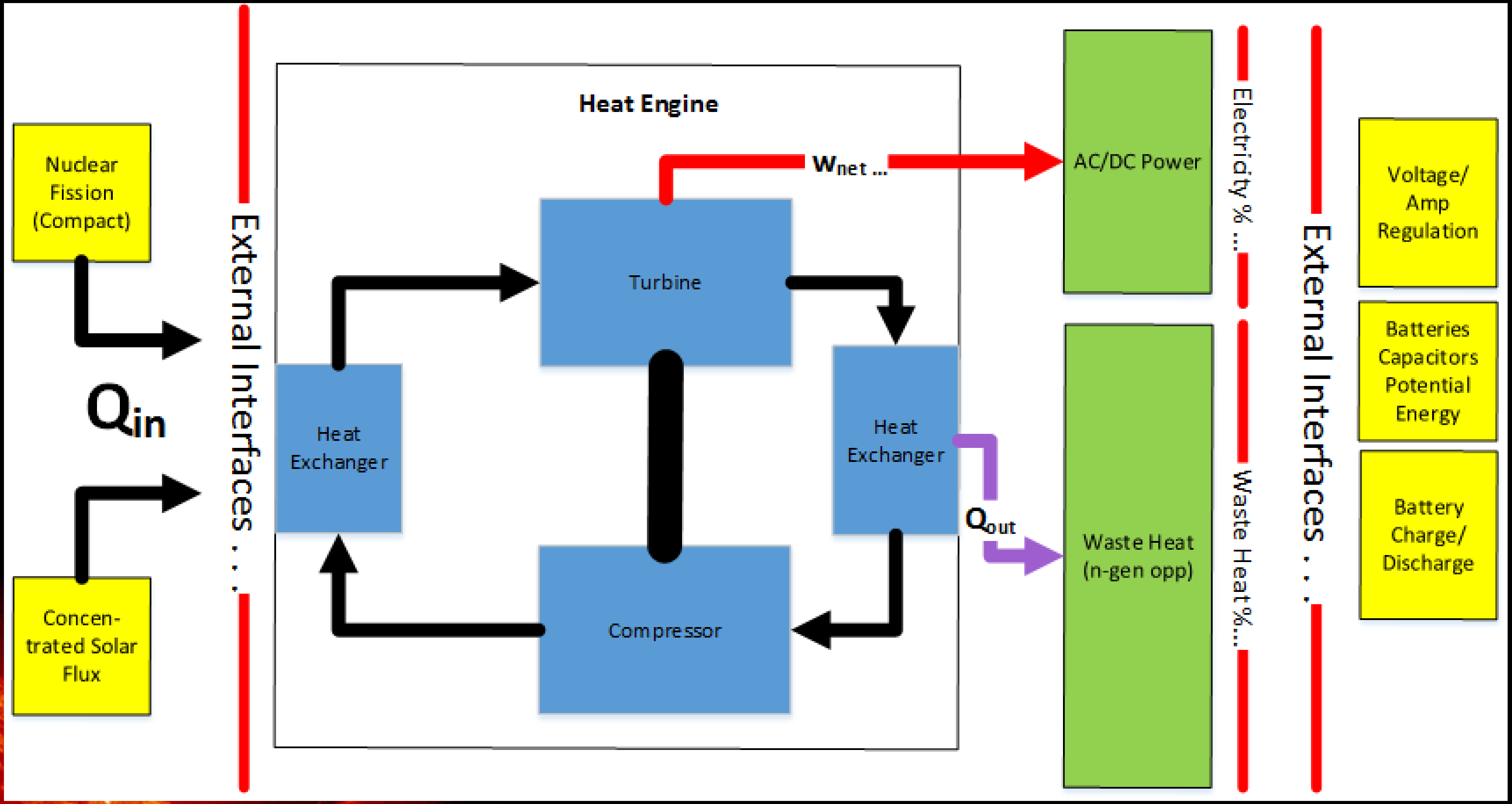
Power Generation, Storage, and Distribution



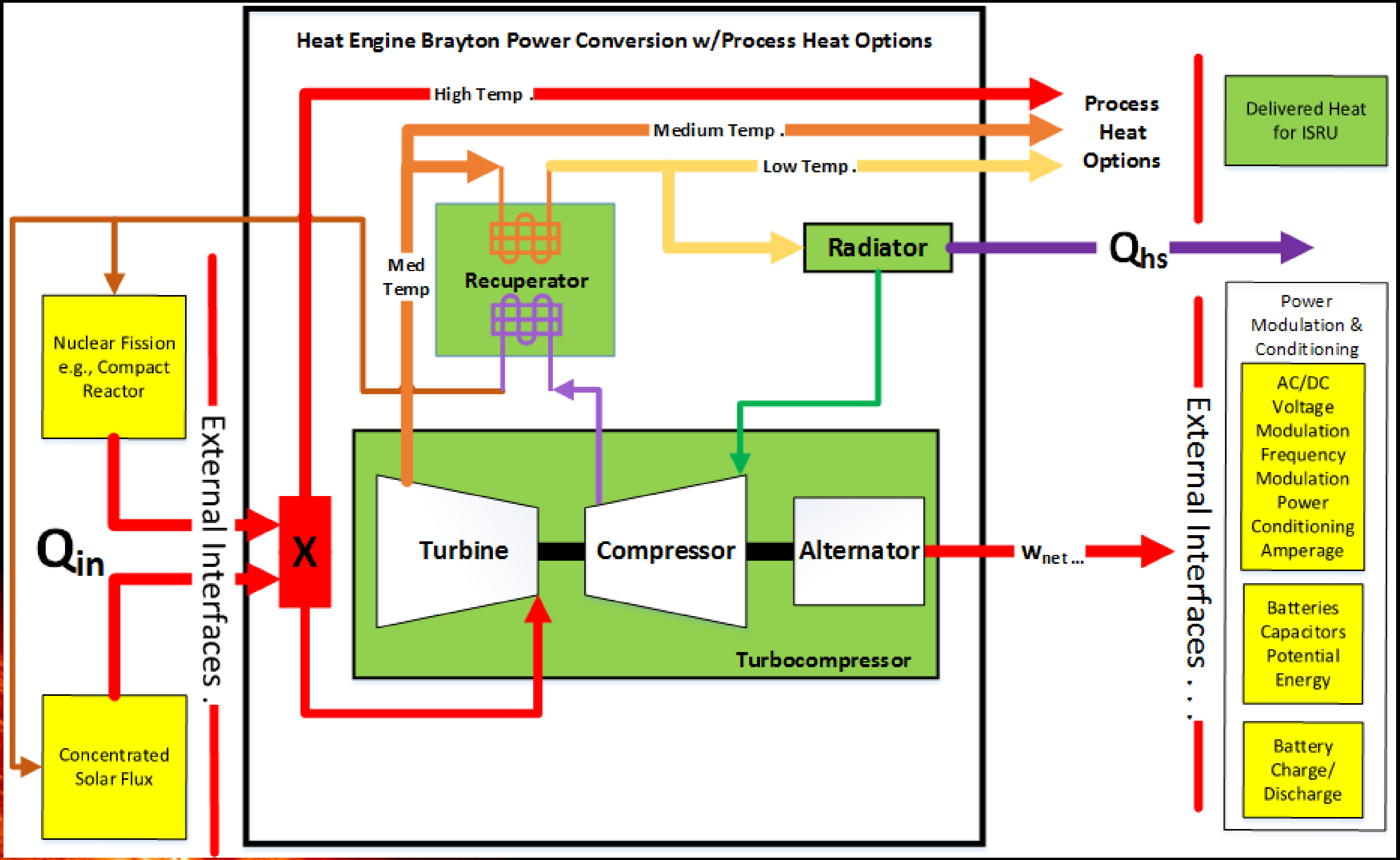
Sustainable Power Generation, Storage, and Distribution



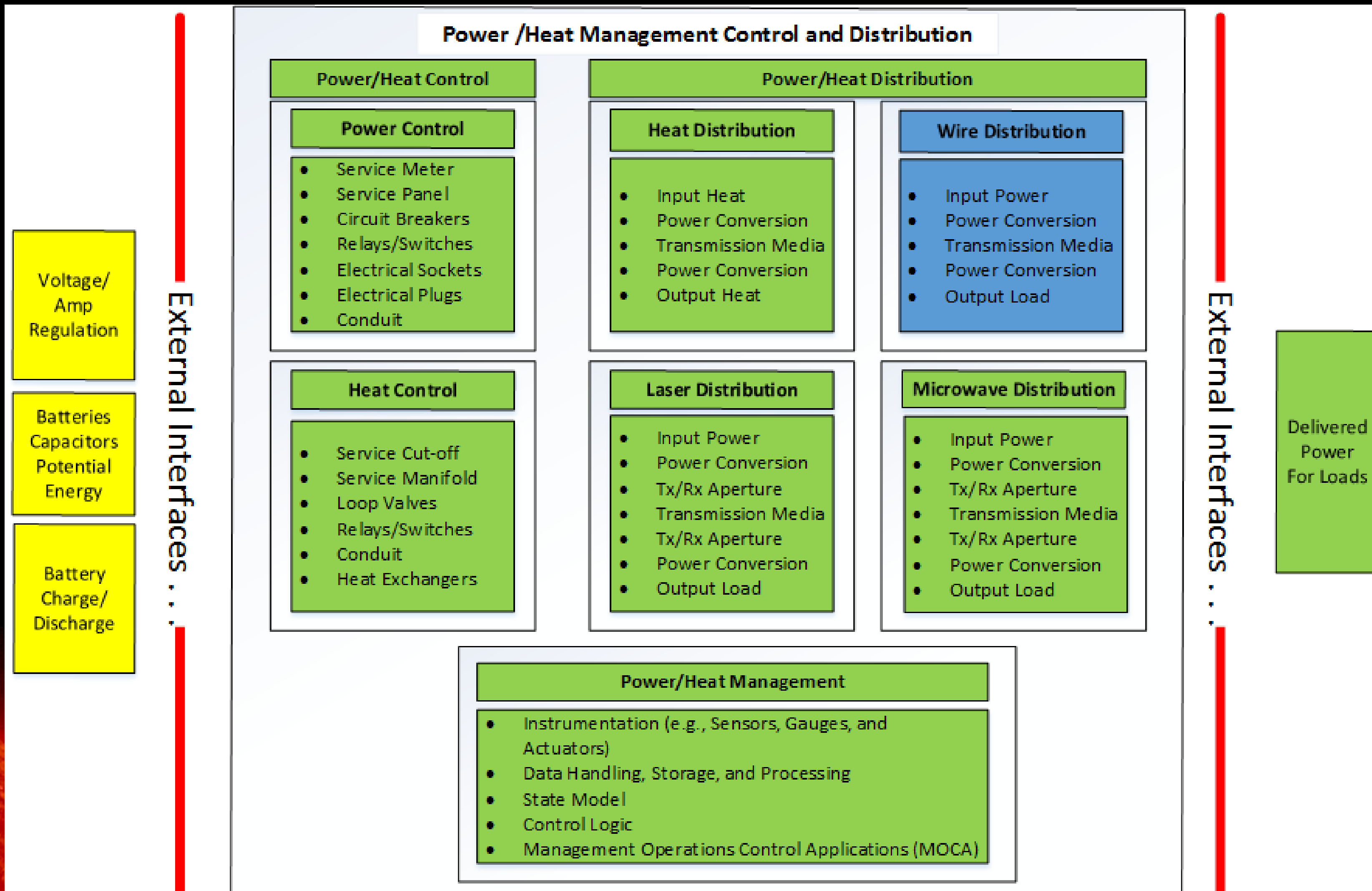
Brayton Cycle Heat Engine Block Diagram (Simple)



Brayton Cycle Hear Engine Block Diagram w/Process Heat Options



SSPB Transceiver Preliminary Design Isometric



Energy TD^3 Iterative and Recursive Milestones

Technology Development → Technology Demonstration → Technology Deployment

Space Solar Power	2019	2022	2025	2029	2038	2047
	ISS TD^3	LEO TD^3	GEO TD^3	GEO TD^3	GEO TD^3	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		
• Space-to-Space	NASA/DOD	NASA/DOD/DOE	NASA/DOD/DOE	Electrical Utility		
• Space-to-Luna	Commercial	Commercial	Commercial	Commercial		
• Space-to-Earth						
• Space-to-NEO	Co-orbiting Test	ComSats Recovery	ComSats Primary	→ $$$	→ $$$$	
• Space In situ	Platform Model	Platform TD^3	Platform Ops	→ $$$	→ $$$$	
• Luna-to-Luna	Spectrum Model	Spectrum Apply	Spectrum Allocation			
• Earth-to-Earth	Orbit Slot Model	Orbit Slot Apply	Orbit Slot Allocation			
	LP&L Seed/Angel	LP&L Series A/B/C	LP&L IPO	→ $$$	→ $$$$	
	Co-orbiting Tests	Co-orbiting Labs	Co-orbiting Facilities	→ $$$	→ $$$$	
		Lunar Test(s)	Lunar Operations	→ $$$	→ $$$$	
		NEO Test(s)	Asteroidal Assay	→ $$$	→ $$$$	

17

Next Steps

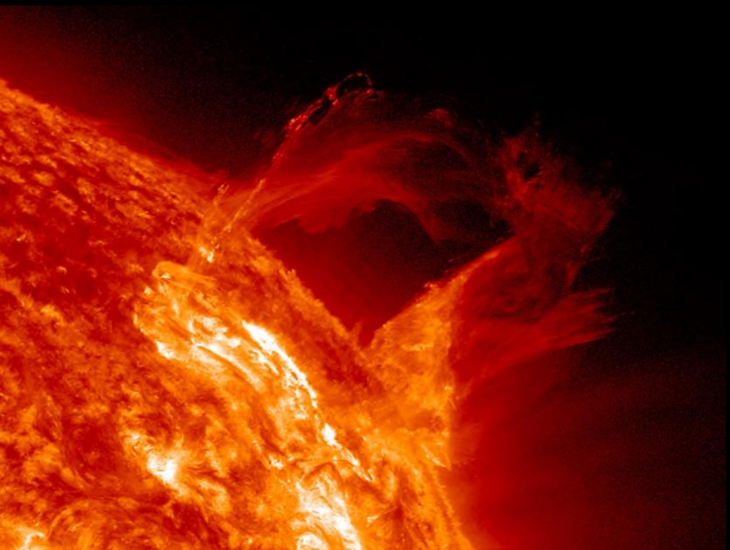
- SSPB is an XISP-Inc commercial TD^3 mission moving forward with the advice and consent of NASA HEOMD.
- Requests for allocation of ISS National Lab/CASIS ISS Resources, Commercial Cargo space, ISS Integration Support, and mission development investment have been formally submitted.
- NASA may participate indirectly through ISS National Lab/CASIS and/or through one or more direct means (e.g., contracts for services/data, ISS Intergovernmental Agreements, funding to accelerate and/or add additional milestones).
- In parallel, to provide an assured path to execution a direct commercial purchase of services agreement is being worked consistent with the forthcoming NASA ISS commercialization policy.
- Additional partners/participants are being sought across the commercial, academic, non-profit, and government sectors.
- Opportunities for international cooperation leveraging the ISS Intergovernmental Agreements are being developed.
- Balance of funding (cash & In-kind) will be raised from the SSPB consortium investments, and XISP-Inc debt/equity financing.

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.

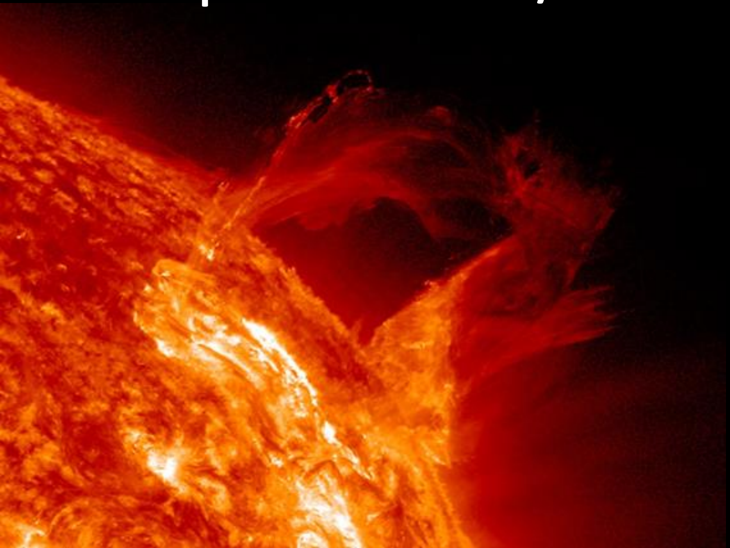
Don't wait for the future, help us make it!

Backup Slides



SSPB 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

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.

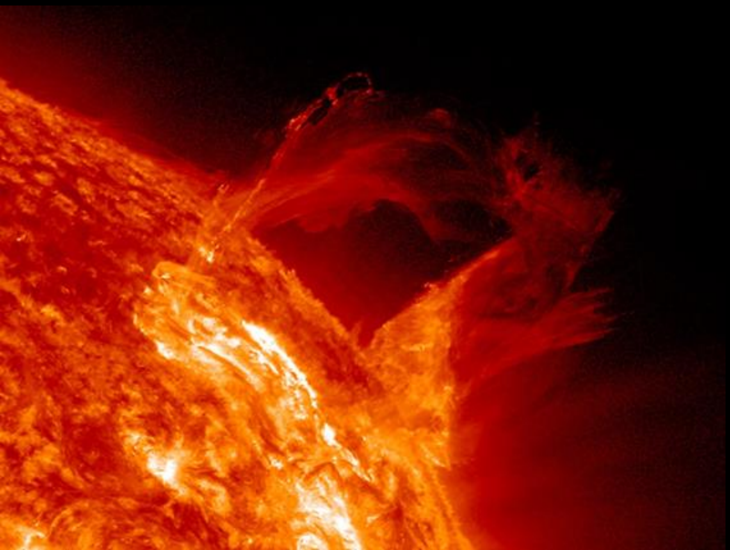
Theoretical Maximum Possible DC to DC Efficiency
Circa 1992 ~76%
Circa 2016 85-95%*** @ < 6 GHz and TBD @ Higher Frequencies
Experimental DC to DC Efficiency Circa 1992 ~54 %, Circa 2016 TBD but significantly higher

*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

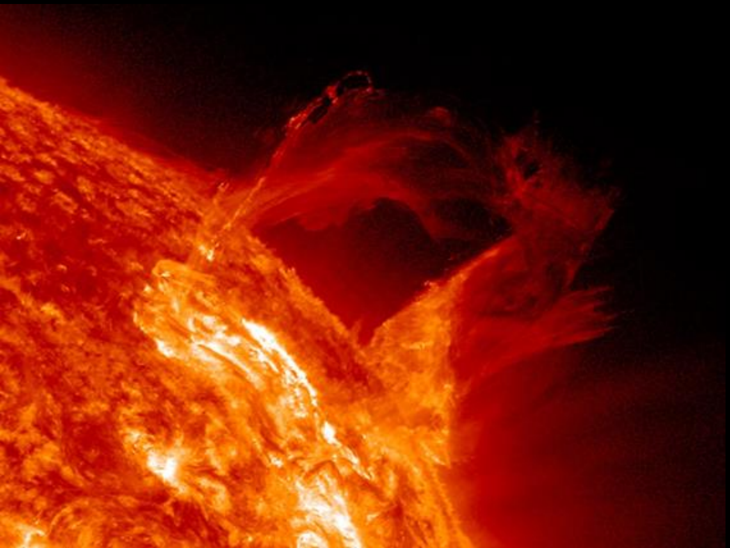
2017 – 60kW combined fiber laser mobile system fielded – Lockheed Martin & U.S. Army

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

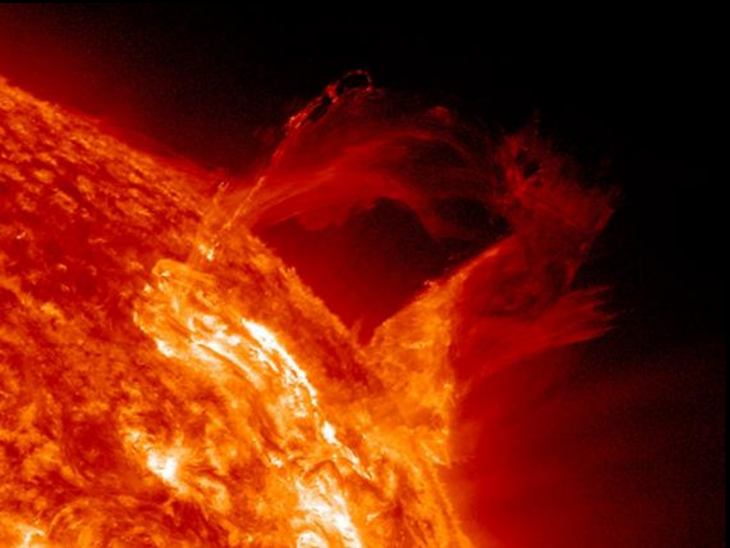
D^2 is the separation between the apertures squared

*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

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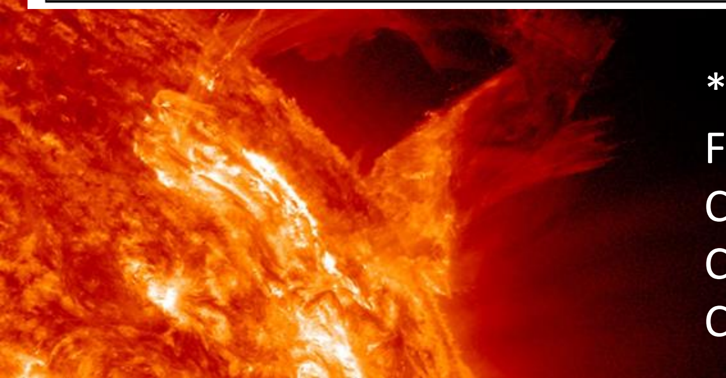
Power Density* - More Optimal Solutions

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

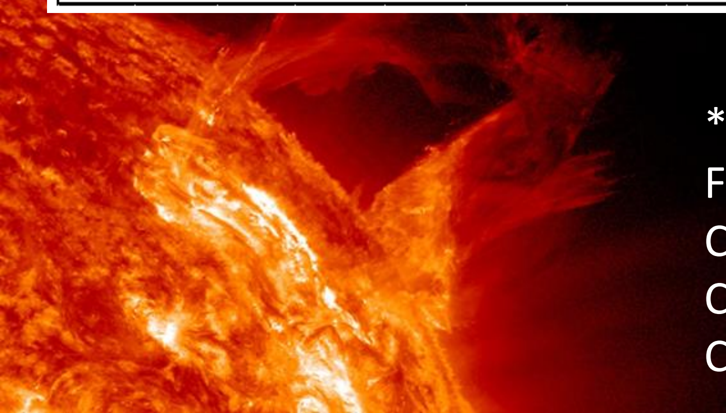
Power Density* - More Optimal Solutions

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

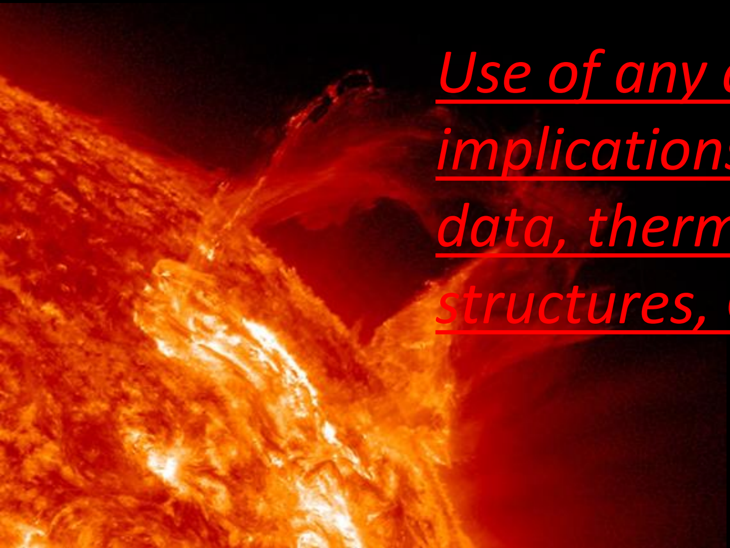
Technological Challenges

- 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

- <u>Economics</u>

– 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.

- <u>Public/Private Partnerships</u>

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

- <u>GeoPolictical</u>

– Make International Cooperation/Collaboration real.

The Evolving XISP-Inc Team . . .

<u>XISP-Inc SSPB Core Team</u>

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

<u>Additional XISP-Inc Staff & Consultants</u>

- 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