Space-to-Space Power Beaming

A Commercial Mission to Unbundle Space Power Systems to Foster Space Applications

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Outline

- **The Problem Addressed - Mission Definition**
  - The Problem
  - The Potential Impacts . . .
  - Relevance to NASA & Others . . .
  - What are we unbundling?
- **The Solution Proposed - Experiment Outline**
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The Problem . . .

XISP-Inc has hypothesized that unbundling 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)

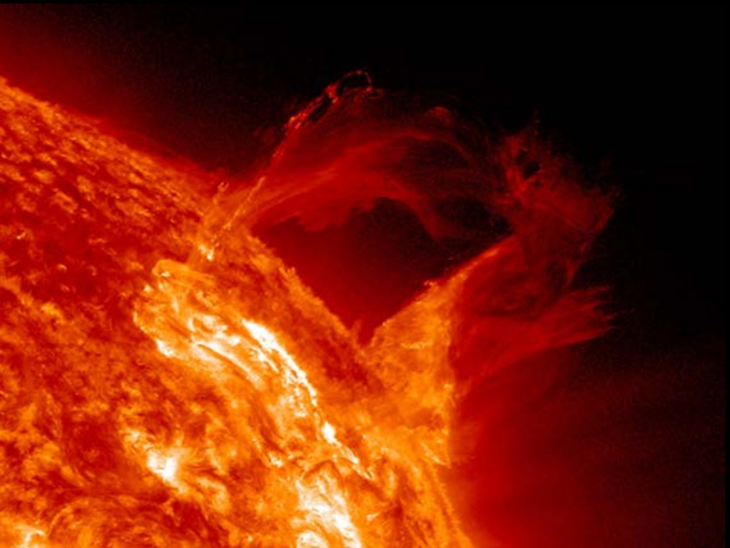
The Potential Impacts . . .

- Mitigating risks can yield more missions and more successful ones
- Fostering the development of loosely coupled modular structures
  - enables large scale adaptable space structures
  - minimizes conducted thermal and/or structural loads
- Facilitating the formation flying of multiple spacecraft
  - enables interferometric groups, swarms, and redundancy
  - creates new data fusion and pattern recognition options
- Simplified distributed payload and subsystem infrastructure
  - enables multiple plug-in and plug-out interfaces
  - opens new opportunities for shared orbital platforms
    - communications
    - remote sensing
    - navigation
    - power

Relevance to NASA & Others - 1

This work is part of a commercial technology development mission being planned for the International Space Station (ISS) which:

- Leverages available ISS resources to serve as a testbed,
- Simultaneously supports payload experiments, and
- Serves to help mitigate perceived cost, schedule, and technical risk associated with the use of Space Solar Power technology.



Relevance to NASA & Others - 2

- This work is part of an overarching Space Act Umbrella Agreement under negotiation between NASA Headquarters and XISP-Inc, for which the Commercial Space-to-Space Power Beaming (SSPB) mission is an Annex, as well as an in-place NASA ARC Space Act Agreement for Mission Operations Control Applications (MOCA).
- The XISP-Inc Commercial SSPB mission using cubesat targets to demonstrate power beaming from ISS requires the cooperation of NASA, Industry, academia, and international partners.

The work will result in a near term demonstration of space-to-space power beaming, and provide a test bed to allow for the rapid iteration of designs and experiments.

Relevance to NASA & Others - 3

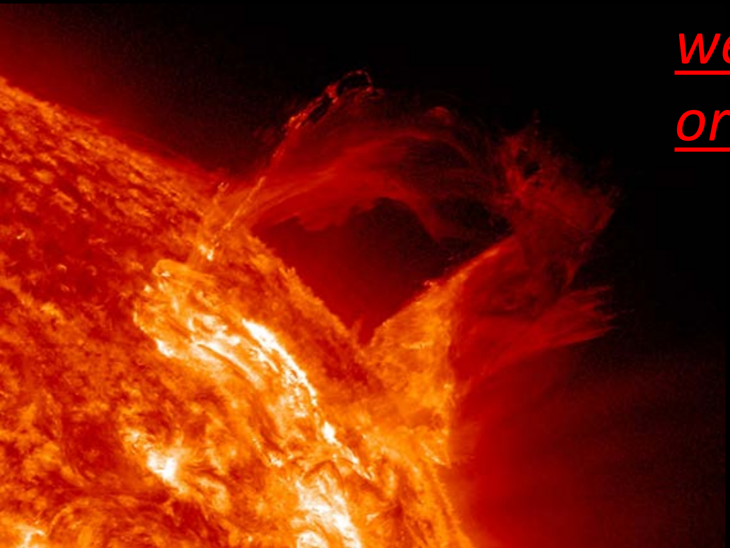
- Establishing a functioning ISS power beaming testbed could allow experimentation and validation of components of larger power beaming systems, and reduce the risk of the development of the larger dedicated systems.
- Although the experiments with ISS and cubesats would be small scale, there could be immediate applications for subsatellites near ISS, repurposed logistics carriers serving as co-orbiting free-flyer manufacturing cells, as well as designs for distributed payloads and sensors for deep space missions including lunar and asteroidal assay work.

The ISS is an extraordinary resource that can be leveraged to dramatically lower the cost of space solar power technology development.

What are we unbundling?

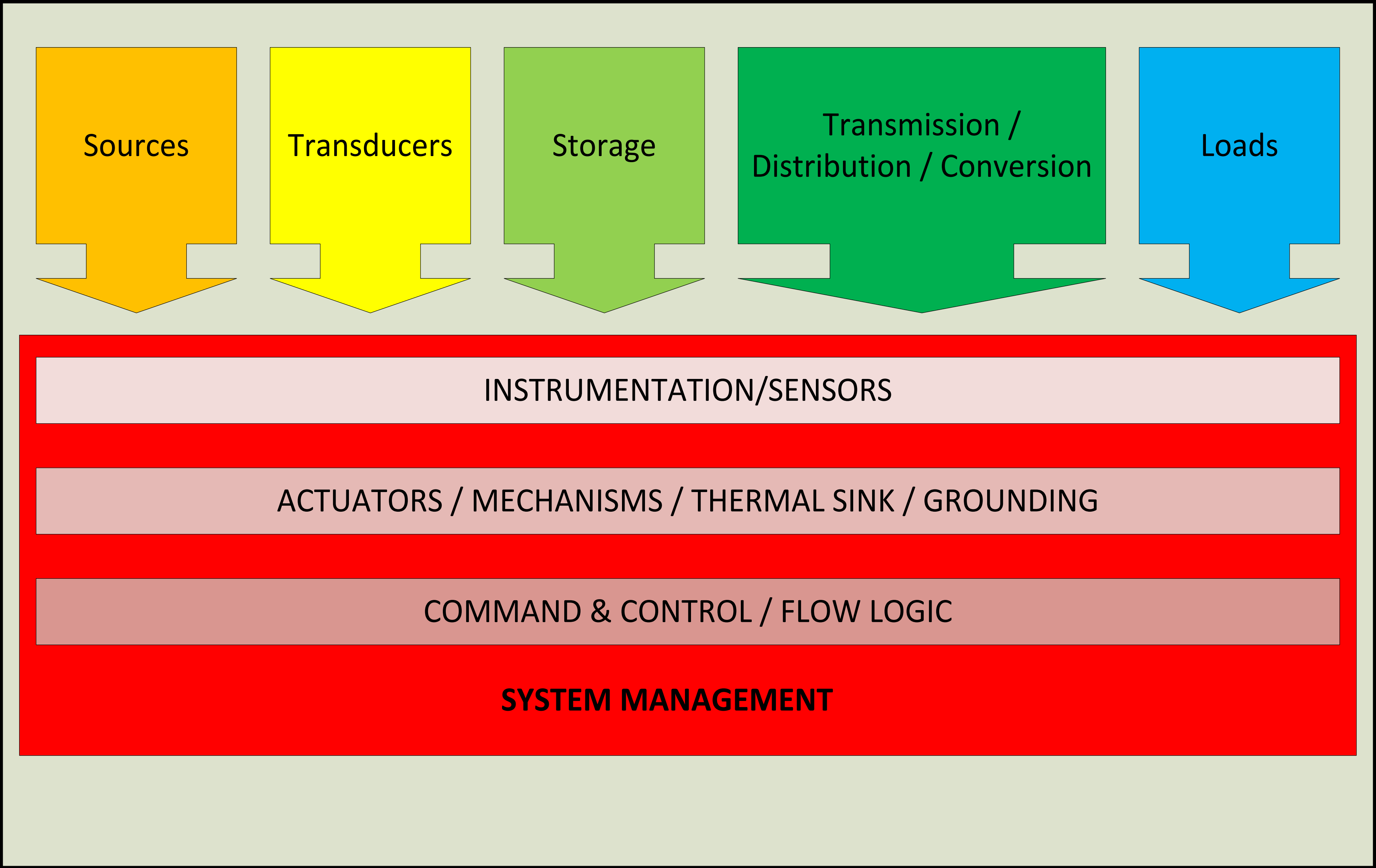
- The Power System block diagram provides a top level view of the subsystems / functional components of a spacecraft electrical power system.

- This is not a mundane academic exercise.



There is a need to structure and order the knowledge of what is known, as well as what is known to be unknown in order to make this analysis tractable.

Power System Block Diagram



Experiment Objectives

(1) Demonstrate space-to-space power beaming by powering first one then multiple co-orbiting spacecraft initially using International Space Station (ISS) based Ka band → W band transmitters.

(2) Demonstrate the successful characterization as well as the direct and indirect use of radiant energy “beam” components.

(3) Reduce the cost, schedule, and technical risk associated with the use of the space solar power technology to better address the mission challenges for a new spacecraft and/or infrastructure.

SSPB Test Bed Experiments

- End-to-End & Piecewise Efficiency Optimization
  - DC ===> Microwave,
  - Beam Forming, Transmission, Rectenna
  - Microwave ===> DC
- 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 Requirements

- Asteroidal Assay
  - Co-orbiting motherships
- ISS Co-orbiting Free-flyers
  - Micro-g manufacturing cells
- 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

Mathematics of Power Beaming* - Efficiency

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)

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

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	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	**=**	**Pd**	*****	**Ar**			
200 m	Pr	=	0.117472	*	**100**	=	**11.75**	watts
200 m	Pr	=	0.117472	*	**200**	=	**23.49**	watts
200 m	Pr	=	0.117472	*	**300**	=	**35.24**	watts
200 m	Pr	=	0.117472	*	**400**	=	**46.99**	watts
200 m	Pr	=	0.117472	*	**500**	=	**58.74**	watts
200 m	Pr	=	0.117472	*	**600**	=	**70.48**	watts
200 m	Pr	=	0.117472	*	**700**	=	**82.23**	watts
200 m	Pr	=	0.117472	*	**800**	=	**93.98**	watts
200 m	Pr	=	0.117472	*	**900**	=	**105.72**	watts
200 m	Pr	=	0.117472	*	**1000**	=	**117.47**	watts
200 m	Pr	=	0.117472	*	**2000**	=	**234.94**	watts
200 m	Pr	=	0.117472	*	**3000**	=	**352.42**	watts
200 m	Pr	=	0.117472	*	**4000**	=	**469.89**	watts
200 m	Pr	=	0.117472	*	**5000**	=	**587.36**	watts
200 m	Pr	=	0.117472	*	**6000**	=	**704.83**	watts
200 m	Pr	=	0.117472	*	**7000**	=	**822.30**	watts
200 m	Pr	=	0.117472	*	**8000**	=	**939.78**	watts
200 m	Pr	=	0.117472	*	**9000**	=	**1057.25**	watts
200 m	Pr	=	0.117472	*	**10000**	=	**1174.72**	watts

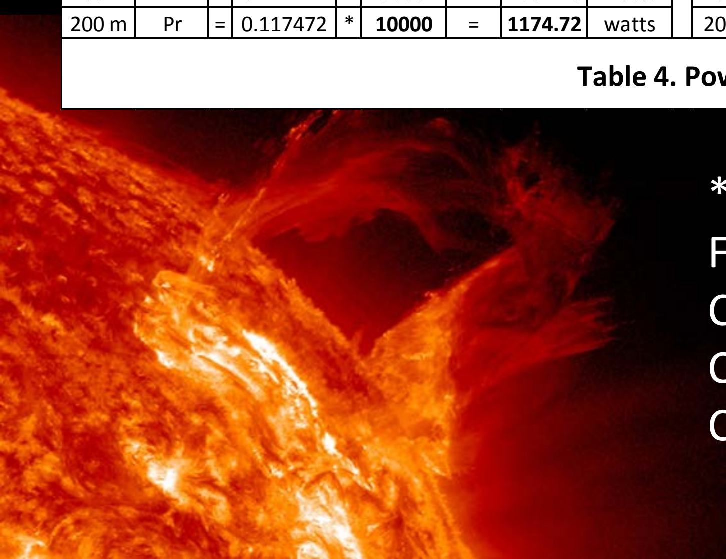
CASE 2 - Space Station Ka Band Transmitter Anticipated Power Received for various rectenna areas - Ka Target 36 GHz

Distance	Power Receive		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	**=**	**Pd**	*****	**Ar**			
200 m	Pr	=	0.2161729	*	**100**	=	**21.62**	watts
200 m	Pr	=	0.2161729	*	**200**	=	**43.23**	watts
200 m	Pr	=	0.2161729	*	**300**	=	**64.85**	watts
200 m	Pr	=	0.2161729	*	**400**	=	**86.47**	watts
200 m	Pr	=	0.2161729	*	**500**	=	**108.09**	watts
200 m	Pr	=	0.2161729	*	**600**	=	**129.70**	watts
200 m	Pr	=	0.2161729	*	**700**	=	**151.32**	watts
200 m	Pr	=	0.2161729	*	**800**	=	**172.94**	watts
200 m	Pr	=	0.2161729	*	**900**	=	**194.56**	watts
200 m	Pr	=	0.2161729	*	**1000**	=	**216.17**	watts
200 m	Pr	=	0.2161729	*	**2000**	=	**432.35**	watts
200 m	Pr	=	0.2161729	*	**3000**	=	**648.52**	watts
200 m	Pr	=	0.2161729	*	**4000**	=	**864.69**	watts
200 m	Pr	=	0.2161729	*	**5000**	=	**1080.86**	watts
200 m	Pr	=	0.2161729	*	**6000**	=	**1297.04**	watts
200 m	Pr	=	0.2161729	*	**7000**	=	**1513.21**	watts
200 m	Pr	=	0.2161729	*	**8000**	=	**1729.38**	watts
200 m	Pr	=	0.2161729	*	**9000**	=	**1945.56**	watts
200 m	Pr	=	0.2161729	*	**10000**	=	**2161.73**	watts

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

Distance	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	**=**	**Pd**	*****	**Ar**			
200 m	Pr	=	1.502163	*	**100**	=	**150.22**	watts
200 m	Pr	=	1.502163	*	**200**	=	**300.43**	watts
200 m	Pr	=	1.502163	*	**300**	=	**450.65**	watts
200 m	Pr	=	1.502163	*	**400**	=	**600.87**	watts
200 m	Pr	=	1.502163	*	**500**	=	**751.08**	watts
200 m	Pr	=	1.502163	*	**600**	=	**901.30**	watts
200 m	Pr	=	1.502163	*	**700**	=	**1051.51**	watts
200 m	Pr	=	1.502163	*	**800**	=	**1201.73**	watts
200 m	Pr	=	1.502163	*	**900**	=	**1351.95**	watts
200 m	Pr	=	1.502163	*	**1000**	=	**1502.16**	watts
200 m	Pr	=	1.502163	*	**2000**	=	**3004.33**	watts
200 m	Pr	=	1.502163	*	**3000**	=	**4506.49**	watts
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~**4000**~~	~~=~~	~~**6008.65**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~**5000**~~	~~=~~	~~**7510.82**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~**6000**~~	~~=~~	~~**9012.98**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~**7000**~~	~~=~~	~~**10515.14**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~**8000**~~	~~=~~	~~**12017.30**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~**9000**~~	~~=~~	~~**13519.47**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~**10000**~~	~~=~~	~~**15021.63**~~	~~watts~~

Table 4. Power Received with 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

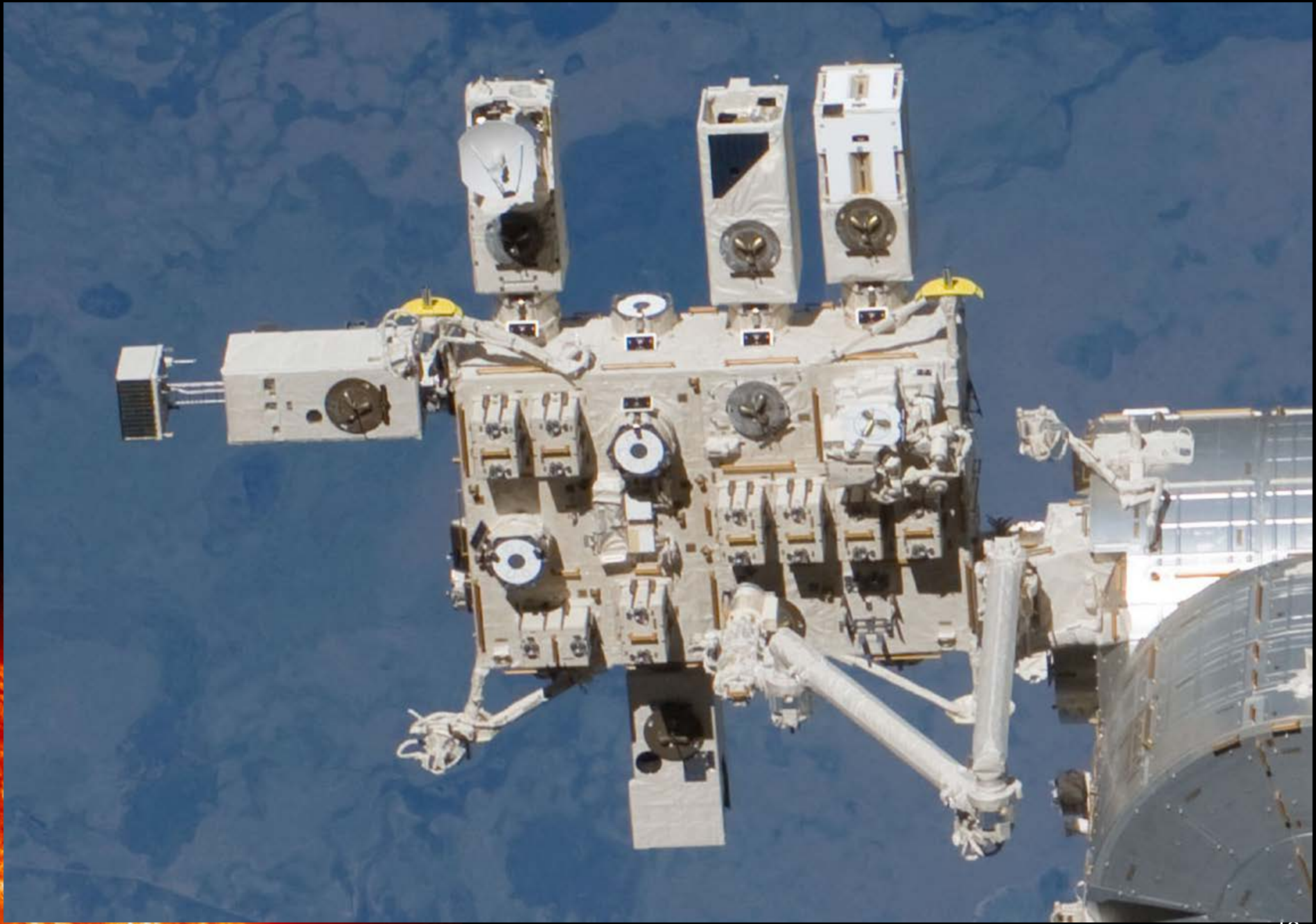
Rectenna Design Elements

- Rectenna Areas
  - 100 cm^2 (1 U) to 1 m^2 (100 U)
- Rectenna Types
  - 2D Rectangular, Polarized Spiral, Fractal, etc.
  - 3D Pyramid, Conical, Fractal, etc.
  - Reflectarray and photovoltaic combinations
- Build Options
  - Earth manufactured, deployed on-orbit
  - Earth manufactured, assembled on-orbit
  - 3D Printed on-orbit

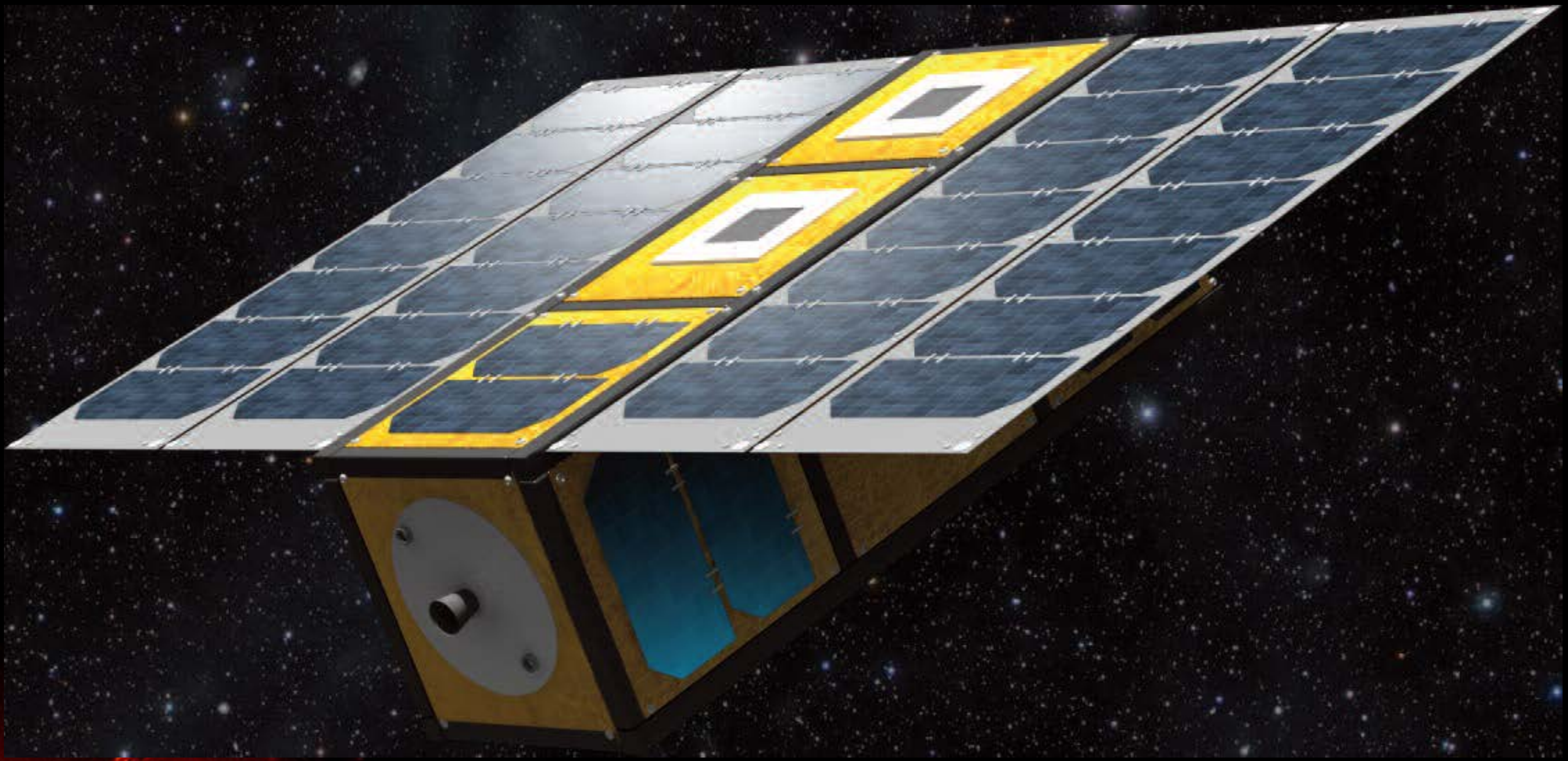
JAXA Inter-orbit Comm System (ICS-EF)

Terrestrial 95 GHz Transmitter (AFRL Design)

JEM Exposed Facility Accommodations

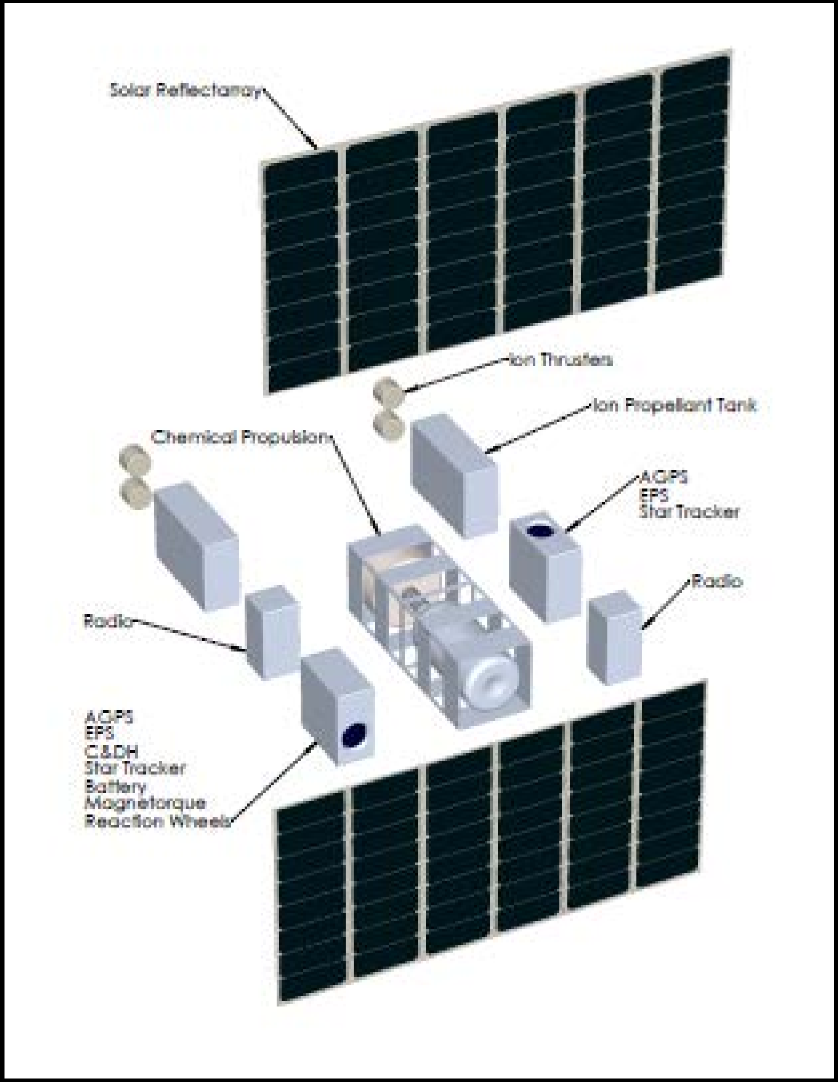


XISP-Inc/DSI 3U SSPB Flight Test Article Concept*



* Shown with DSI COMET-1 Water Thruster Integrated. Flight articles used will incorporate Reflectarray Rectennas (combination solar/receive & transmit antennas).

Alpha CubeSat Derived Flight Test Articles*



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

Experiment Work Vectors

(1) Deep Space Industries will provide initial flight test articles in return for testing to their asteroid assay requirements.
(2) Available MCT/WARP software toolkit will be extended to support integrated end-to-end mission operations control applications for technology development research.
(3) Multiple university & commercial research and technology development efforts on rectenna design and microwave transmitter optimization will be leveraged to assist in design.
(4) Multiple university & NASA cubesat research and technology development efforts on spacecraft optimization will be recursively extended by creating testbed opportunities.
(5) Enhanced flight test articles derived from the Team Alpha CubeSat mission will support further commercial/science use.
(6) Testbed work is the foundation for ISS co-orbiting free flyers.

Cygnus & Dragon Free flyers

Orbital ATK

SPACEX

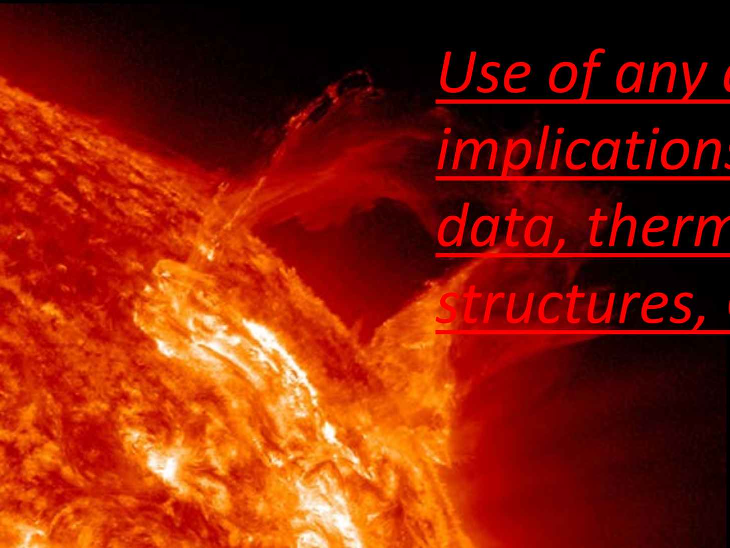
Technological Challenges

- The first principles physics of both near field and far field energy effects are considered well understood.
- However, the use of radiant energy (by definition a Far field effect, a.k.a. "Beaming") to transfer (power, data, force, heat) either directly and/or by inducing near field effects at a distance is less understood at least from the stand point 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

The Evolving SSPB Team . . .

- Xtraordinary Innovative Space Partnerships, Inc. - Gary Barnhard, et.al.
- Deep Space Industries, Inc - Daniel Faber, et.al.
- Center for the Advancement of Science In Space (CASIS)
- Nanoracks Inc. – Chad Brinkley, et.al.
- EXOS Aerospace – John Quinn, et.al.
- University of New Mexico Configurable Space Microsystems Innovations and Applications Center (COSMIAC) - Christos Christodoulou, et.al.
- University of Maryland Space Systems Lab - David Akin, et.al
- University of North Dakota Space Systems Lab - Sima Noghanian, et.al.
- Saint Louis University Space Systems Lab – Michael Swartwout, et.al.
- Zero Gravity Solutions - Rich Godwin, et.al.
- Naval Systems Research Lab - Paul Jaffe, et.al
- Other Advisors – Paul Werbos, Seth Potter, Joseph Rauscher, 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.

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

Next Steps

- SSPB is a XISP-Inc commercial mission recognized by NASA.
- NASA is participating through a combination of in-place (NASA ARC) and proposed (NASA HQ) Space Act Agreements.
- Formal request for support is under review with CASIS.
- NASA direct support to accelerate and/or add additional milestones when opportunities emerge is being negotiated.
- Additional partners/participants are being sought in the commercial, academic, non-profit, and government sectors.
- Opportunities for international cooperation leveraging the ISS Intergovernmental Agreement are being explored and developed.

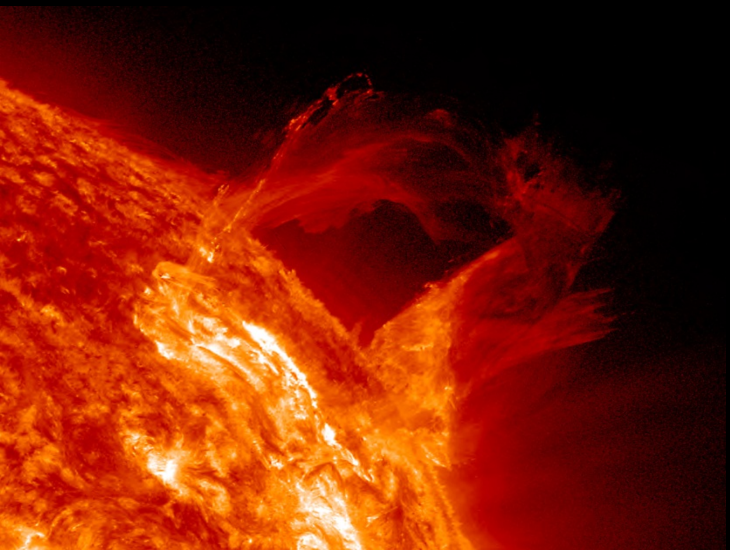
Use of ISS helps ensure that this is an international cooperative/collaborative research effort.

Conclusion

Successful demonstration of space solar power beaming helps pave the way for it's use in a range of space-to-space, space-to-lunar/infrastructure surface, and space-to-Earth applications by reducing the perceived cost, schedule, and technical risk of the technology.

Commercial space applications include mission enhancing and/or mission enabling expansion of operational mission time/capabilities, enhanced spacecraft/infrastructure design flexibility as well as out-bound orbital trajectory insertion propulsion.

Backup Slides



SSPB Experiment Overlay

- Primary Source: Solar flux, LEO
- Transducer: ISS Power System, photovoltaic cells
- Storage: ISS Power System, batteries
- Transmission: ISS Power System, PMAD to JEM EF Utility Port

    \- -

    - **Input Power: 3 Kw, JEM Exposed Facility Port**
    - **DC Power to Microwave Conversion**
    - **Beam Forming Antenna**
    - **Free Space Transmission**
    - **Reception Conversion to DC**
    - **Delivered Power to Spacecraft Power System Bus**

        \- -

        - Spacecraft Loads

What's New with the SSPB Mission?

- <u>Mission Definition</u>
  - Concept of Operations is more detailed
  - <u>Technical Team</u>
    - Link to CubeQuest Challenge Team Alpha CubeSat
    - Interest from all sectors continues to grow
    - Architecting and making collaboration work is a challenge
    - <u>Resources & Schedule</u>
      - NASA has classified SSPB as a Commercial Mission
      - NASA's level and type of participation is under negotiation
      - NASA has acknowledged and is cognizant of formal CASIS resource request (mission development, integration, launch, ISS equipment, and ISS crew time).
      - <u>Experiment Details</u>
        - Social media videos
        - Flight Test Article Designs
        - Testbed Experiments
        - <u>Commercial Requirements</u>
          - New and better defined requirements

Experiment Description

- This experiment set will give mission users an enhanced alternate power supply and substantiate further development of power beaming technology.
- This experiment is an opportunity to craft viable technology demonstrations that will establish the basis for a confluence of interest between real mission users and the technology development effort.
- The results of this effort will lead to the effective use of beamed energy to support:
  - sustained operations,
  - directly and/or indirectly augmented propulsion,
  - loosely coupled modular structures, and
  - new opportunities for advanced modular infrastructure

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	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	**=**	**Pd**	*****	**Ar**			
200 m	Pr	=	0.009643	*	**100**	=	**0.96**	watts
200 m	Pr	=	0.009643	*	**200**	=	**1.93**	watts
200 m	Pr	=	0.009643	*	**300**	=	**2.89**	watts
200 m	Pr	=	0.009643	*	**400**	=	**3.86**	watts
200 m	Pr	=	0.009643	*	**500**	=	**4.82**	watts
200 m	Pr	=	0.009643	*	**600**	=	**5.79**	watts
200 m	Pr	=	0.009643	*	**700**	=	**6.75**	watts
200 m	Pr	=	0.009643	*	**800**	=	**7.71**	watts
200 m	Pr	=	0.009643	*	**900**	=	**8.68**	watts
200 m	Pr	=	0.009643	*	**1000**	=	**9.64**	watts
200 m	Pr	=	0.009643	*	**2000**	=	**19.29**	watts
200 m	Pr	=	0.009643	*	**3000**	=	**28.93**	watts
200 m	Pr	=	0.009643	*	**4000**	=	**38.57**	watts
200 m	Pr	=	0.009643	*	**5000**	=	**48.21**	watts
200 m	Pr	=	0.009643	*	**6000**	=	**57.86**	watts
200 m	Pr	=	0.009643	*	**7000**	=	**67.50**	watts
200 m	Pr	=	0.009643	*	**8000**	=	**77.14**	watts
200 m	Pr	=	0.009643	*	**9000**	=	**86.79**	watts
200 m	Pr	=	0.009643	*	**10000**	=	**96.43**	watts

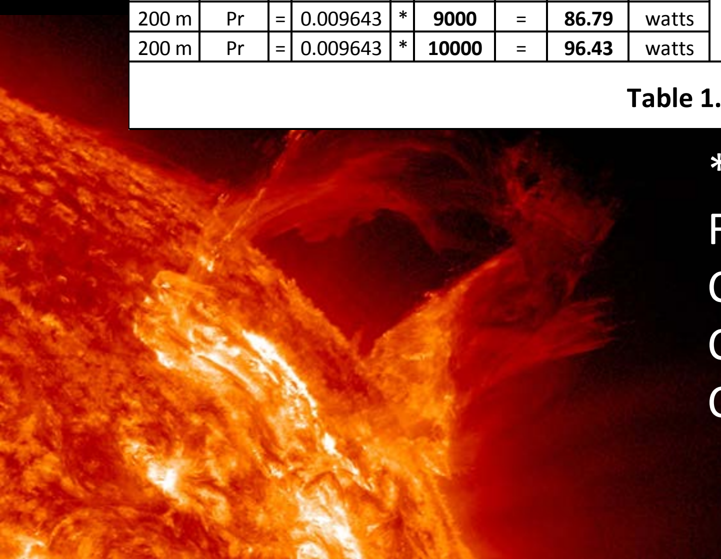
CASE 2 - Space Station Ka Band Transmitter Anticipated Power Received for various rectenna areas - Ka Target 36 GHz

Distance	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	**=**	**Pd**	*****	**Ar**			
200 m	Pr	=	0.017745	*	**100**	=	**1.77**	watts
200 m	Pr	=	0.017745	*	**200**	=	**3.55**	watts
200 m	Pr	=	0.017745	*	**300**	=	**5.32**	watts
200 m	Pr	=	0.017745	*	**400**	=	**7.10**	watts
200 m	Pr	=	0.017745	*	**500**	=	**8.87**	watts
200 m	Pr	=	0.017745	*	**600**	=	**10.65**	watts
200 m	Pr	=	0.017745	*	**700**	=	**12.42**	watts
200 m	Pr	=	0.017745	*	**800**	=	**14.20**	watts
200 m	Pr	=	0.017745	*	**900**	=	**15.97**	watts
200 m	Pr	=	0.017745	*	**1000**	=	**17.74**	watts
200 m	Pr	=	0.017745	*	**2000**	=	**35.49**	watts
200 m	Pr	=	0.017745	*	**3000**	=	**53.23**	watts
200 m	Pr	=	0.017745	*	**4000**	=	**70.98**	watts
200 m	Pr	=	0.017745	*	**5000**	=	**88.72**	watts
200 m	Pr	=	0.017745	*	**6000**	=	**106.47**	watts
200 m	Pr	=	0.017745	*	**7000**	=	**124.21**	watts
200 m	Pr	=	0.017745	*	**8000**	=	**141.96**	watts
200 m	Pr	=	0.017745	*	**9000**	=	**159.70**	watts
200 m	Pr	=	0.017745	*	**10000**	=	**177.45**	watts

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

Distance	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	**=**	**Pd**	*****	**Ar**			
200 m	Pr	=	0.123307	*	**100**	=	**12.33**	watts
200 m	Pr	=	0.123307	*	**200**	=	**24.66**	watts
200 m	Pr	=	0.123307	*	**300**	=	**36.99**	watts
200 m	Pr	=	0.123307	*	**400**	=	**49.32**	watts
200 m	Pr	=	0.123307	*	**500**	=	**61.65**	watts
200 m	Pr	=	0.123307	*	**600**	=	**73.98**	watts
200 m	Pr	=	0.123307	*	**700**	=	**86.32**	watts
200 m	Pr	=	0.123307	*	**800**	=	**98.65**	watts
200 m	Pr	=	0.123307	*	**900**	=	**110.98**	watts
200 m	Pr	=	0.123307	*	**1000**	=	**123.31**	watts
200 m	Pr	=	0.123307	*	**2000**	=	**246.61**	watts
200 m	Pr	=	0.123307	*	**3000**	=	**369.92**	watts
200 m	Pr	=	0.123307	*	**4000**	=	**493.23**	watts
200 m	Pr	=	0.123307	*	**5000**	=	**616.54**	watts
200 m	Pr	=	0.123307	*	**6000**	=	**739.84**	watts
200 m	Pr	=	0.123307	*	**7000**	=	**863.15**	watts
200 m	Pr	=	0.123307	*	**8000**	=	**986.46**	watts
200 m	Pr	=	0.123307	*	**9000**	=	**1109.77**	watts
200 m	Pr	=	0.123307	*	**10000**	=	**1233.07**	watts

Table 1. Power Received with P_t= 3000 W and A_t = 1642 cm^2



*Power Received with P_t = 3000 W and A_t = 1642 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	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	**=**	**Pd**	*****	**Ar**			
200 m	Pr	=	0.019286	*	**100**	=	**1.93**	watts
200 m	Pr	=	0.019286	*	**200**	=	**3.86**	watts
200 m	Pr	=	0.019286	*	**300**	=	**5.79**	watts
200 m	Pr	=	0.019286	*	**400**	=	**7.71**	watts
200 m	Pr	=	0.019286	*	**500**	=	**9.64**	watts
200 m	Pr	=	0.019286	*	**600**	=	**11.57**	watts
200 m	Pr	=	0.019286	*	**700**	=	**13.50**	watts
200 m	Pr	=	0.019286	*	**800**	=	**15.43**	watts
200 m	Pr	=	0.019286	*	**900**	=	**17.36**	watts
200 m	Pr	=	0.019286	*	**1000**	=	**19.29**	watts
200 m	Pr	=	0.019286	*	**2000**	=	**38.57**	watts
200 m	Pr	=	0.019286	*	**3000**	=	**57.86**	watts
200 m	Pr	=	0.019286	*	**4000**	=	**77.14**	watts
200 m	Pr	=	0.019286	*	**5000**	=	**96.43**	watts
200 m	Pr	=	0.019286	*	**6000**	=	**115.71**	watts
200 m	Pr	=	0.019286	*	**7000**	=	**135.00**	watts
200 m	Pr	=	0.019286	*	**8000**	=	**154.29**	watts
200 m	Pr	=	0.019286	*	**9000**	=	**173.57**	watts
200 m	Pr	=	0.019286	*	**10000**	=	**192.86**	watts

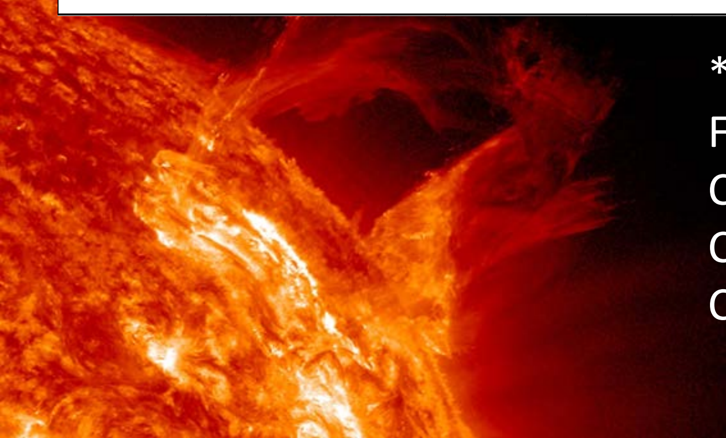
CASE 2 - Space Station Ka Band Transmitter Anticipated Power Received for various rectenna areas - Ka Target 36 GHz

Distance	Power Receive		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	**=**	**Pd**	*****	**Ar**			
200 m	Pr	=	0.035490	*	**100**	=	**3.55**	watts
200 m	Pr	=	0.035490	*	**200**	=	**7.10**	watts
200 m	Pr	=	0.035490	*	**300**	=	**10.65**	watts
200 m	Pr	=	0.035490	*	**400**	=	**14.20**	watts
200 m	Pr	=	0.035490	*	**500**	=	**17.74**	watts
200 m	Pr	=	0.035490	*	**600**	=	**21.29**	watts
200 m	Pr	=	0.035490	*	**700**	=	**24.84**	watts
200 m	Pr	=	0.035490	*	**800**	=	**28.39**	watts
200 m	Pr	=	0.035490	*	**900**	=	**31.94**	watts
200 m	Pr	=	0.035490	*	**1000**	=	**35.49**	watts
200 m	Pr	=	0.035490	*	**2000**	=	**70.98**	watts
200 m	Pr	=	0.035490	*	**3000**	=	**106.47**	watts
200 m	Pr	=	0.035490	*	**4000**	=	**141.96**	watts
200 m	Pr	=	0.035490	*	**5000**	=	**177.45**	watts
200 m	Pr	=	0.035490	*	**6000**	=	**212.94**	watts
200 m	Pr	=	0.035490	*	**7000**	=	**248.43**	watts
200 m	Pr	=	0.035490	*	**8000**	=	**283.92**	watts
200 m	Pr	=	0.035490	*	**9000**	=	**319.41**	watts
200 m	Pr	=	0.035490	*	**10000**	=	**354.90**	watts

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

Distance	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	**=**	**Pd**	*****	**Ar**			
200 m	Pr	=	0.246615	*	**100**	=	**24.66**	watts
200 m	Pr	=	0.246615	*	**200**	=	**49.32**	watts
200 m	Pr	=	0.246615	*	**300**	=	**73.98**	watts
200 m	Pr	=	0.246615	*	**400**	=	**98.65**	watts
200 m	Pr	=	0.246615	*	**500**	=	**123.31**	watts
200 m	Pr	=	0.246615	*	**600**	=	**147.97**	watts
200 m	Pr	=	0.246615	*	**700**	=	**172.63**	watts
200 m	Pr	=	0.246615	*	**800**	=	**197.29**	watts
200 m	Pr	=	0.246615	*	**900**	=	**221.95**	watts
200 m	Pr	=	0.246615	*	**1000**	=	**246.61**	watts
200 m	Pr	=	0.246615	*	**2000**	=	**493.23**	watts
200 m	Pr	=	0.246615	*	**3000**	=	**739.84**	watts
200 m	Pr	=	0.246615	*	**4000**	=	**986.46**	watts
200 m	Pr	=	0.246615	*	**5000**	=	**1233.07**	watts
200 m	Pr	=	0.246615	*	**6000**	=	**1479.69**	watts
200 m	Pr	=	0.246615	*	**7000**	=	**1726.30**	watts
200 m	Pr	=	0.246615	*	**8000**	=	**1972.92**	watts
200 m	Pr	=	0.246615	*	**9000**	=	**2219.53**	watts
200 m	Pr	=	0.246615	*	**10000**	=	**2466.15**	watts

Table 2. Power Received with P_t= 6000 W and A_t = 1642 cm^2



*Power Received with P_t = 6000 W and A_t = 1642 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	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	**=**	**Pd**	*****	**Ar**			
200 m	Pr	=	0.058736	*	**100**	=	**5.87**	watts
200 m	Pr	=	0.058736	*	**200**	=	**11.75**	watts
200 m	Pr	=	0.058736	*	**300**	=	**17.62**	watts
200 m	Pr	=	0.058736	*	**400**	=	**23.49**	watts
200 m	Pr	=	0.058736	*	**500**	=	**29.37**	watts
200 m	Pr	=	0.058736	*	**600**	=	**35.24**	watts
200 m	Pr	=	0.058736	*	**700**	=	**41.12**	watts
200 m	Pr	=	0.058736	*	**800**	=	**46.99**	watts
200 m	Pr	=	0.058736	*	**900**	=	**52.86**	watts
200 m	Pr	=	0.058736	*	**1000**	=	**58.74**	watts
200 m	Pr	=	0.058736	*	**2000**	=	**117.47**	watts
200 m	Pr	=	0.058736	*	**3000**	=	**176.21**	watts
200 m	Pr	=	0.058736	*	**4000**	=	**234.94**	watts
200 m	Pr	=	0.058736	*	**5000**	=	**293.68**	watts
200 m	Pr	=	0.058736	*	**6000**	=	**352.42**	watts
200 m	Pr	=	0.058736	*	**7000**	=	**411.15**	watts
200 m	Pr	=	0.058736	*	**8000**	=	**469.89**	watts
200 m	Pr	=	0.058736	*	**9000**	=	**528.62**	watts
200 m	Pr	=	0.058736	*	**10000**	=	**587.36**	watts

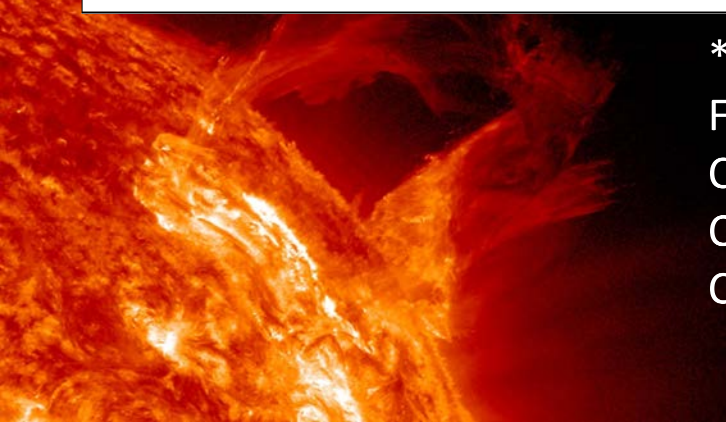
CASE 2 - Space Station Ka Band Transmitter Anticipated Power Received for various rectenna areas - Ka Target 36 GHz

Distance	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	**=**	**Pd**	*****	**Ar**			
200 m	Pr	=	0.108086	*	**100**	=	**10.81**	watts
200 m	Pr	=	0.108086	*	**200**	=	**21.62**	watts
200 m	Pr	=	0.108086	*	**300**	=	**32.43**	watts
200 m	Pr	=	0.108086	*	**400**	=	**43.23**	watts
200 m	Pr	=	0.108086	*	**500**	=	**54.04**	watts
200 m	Pr	=	0.108086	*	**600**	=	**64.85**	watts
200 m	Pr	=	0.108086	*	**700**	=	**75.66**	watts
200 m	Pr	=	0.108086	*	**800**	=	**86.47**	watts
200 m	Pr	=	0.108086	*	**900**	=	**97.28**	watts
200 m	Pr	=	0.108086	*	**1000**	=	**108.09**	watts
200 m	Pr	=	0.108086	*	**2000**	=	**216.17**	watts
200 m	Pr	=	0.108086	*	**3000**	=	**324.26**	watts
200 m	Pr	=	0.108086	*	**4000**	=	**432.35**	watts
200 m	Pr	=	0.108086	*	**5000**	=	**540.43**	watts
200 m	Pr	=	0.108086	*	**6000**	=	**648.52**	watts
200 m	Pr	=	0.108086	*	**7000**	=	**756.61**	watts
200 m	Pr	=	0.108086	*	**8000**	=	**864.69**	watts
200 m	Pr	=	0.108086	*	**9000**	=	**972.78**	watts
200 m	Pr	=	0.108086	*	**10000**	=	**1080.86**	watts

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

Distance	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	**=**	**Pd**	*****	**Ar**			
200 m	Pr	=	0.751082	*	**100**	=	**75.11**	watts
200 m	Pr	=	0.751082	*	**200**	=	**150.22**	watts
200 m	Pr	=	0.751082	*	**300**	=	**225.32**	watts
200 m	Pr	=	0.751082	*	**400**	=	**300.43**	watts
200 m	Pr	=	0.751082	*	**500**	=	**375.54**	watts
200 m	Pr	=	0.751082	*	**600**	=	**450.65**	watts
200 m	Pr	=	0.751082	*	**700**	=	**525.76**	watts
200 m	Pr	=	0.751082	*	**800**	=	**600.87**	watts
200 m	Pr	=	0.751082	*	**900**	=	**675.97**	watts
200 m	Pr	=	0.751082	*	**1000**	=	**751.08**	watts
200 m	Pr	=	0.751082	*	**2000**	=	**1502.16**	watts
200 m	Pr	=	0.751082	*	**3000**	=	**2253.24**	watts
~~200 m~~	~~Pr~~	~~=~~	~~0.751082~~	~~*~~	~~**4000**~~	~~=~~	~~**3004.33**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~0.751082~~	~~*~~	~~**5000**~~	~~=~~	~~**3755.41**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~0.751082~~	~~*~~	~~**6000**~~	~~=~~	~~**4506.49**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~0.751082~~	~~*~~	~~**7000**~~	~~=~~	~~**5257.57**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~0.751082~~	~~*~~	~~**8000**~~	~~=~~	~~**6008.65**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~0.751082~~	~~*~~	~~**9000**~~	~~=~~	~~**6759.73**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~0.751082~~	~~*~~	~~**10000**~~	~~=~~	~~**7510.82**~~	~~watts~~

Table 3. Power Received with 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	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	=	Pd	*	Ar			
200 m	Pr	=	0.117472	*	**100**	=	**11.75**	watts
200 m	Pr	=	0.117472	*	**200**	=	**23.49**	watts
200 m	Pr	=	0.117472	*	**300**	=	**35.24**	watts
200 m	Pr	=	0.117472	*	**400**	=	**46.99**	watts
200 m	Pr	=	0.117472	*	**500**	=	**58.74**	watts
200 m	Pr	=	0.117472	*	**600**	=	**70.48**	watts
200 m	Pr	=	0.117472	*	**700**	=	**82.23**	watts
200 m	Pr	=	0.117472	*	**800**	=	**93.98**	watts
200 m	Pr	=	0.117472	*	**900**	=	**105.72**	watts
200 m	Pr	=	0.117472	*	**1000**	=	**117.47**	watts
200 m	Pr	=	0.117472	*	**2000**	=	**234.94**	watts
200 m	Pr	=	0.117472	*	**3000**	=	**352.42**	watts
200 m	Pr	=	0.117472	*	**4000**	=	**469.89**	watts
200 m	Pr	=	0.117472	*	**5000**	=	**587.36**	watts
200 m	Pr	=	0.117472	*	**6000**	=	**704.83**	watts
200 m	Pr	=	0.117472	*	**7000**	=	**822.30**	watts
200 m	Pr	=	0.117472	*	**8000**	=	**939.78**	watts
200 m	Pr	=	0.117472	*	**9000**	=	**1057.25**	watts
200 m	Pr	=	0.117472	*	**10000**	=	**1174.72**	watts

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

Distance	Power Receive		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	=	Pd	*	Ar			
200 m	Pr	=	0.2161729	*	**100**	=	**21.62**	watts
200 m	Pr	=	0.2161729	*	**200**	=	**43.23**	watts
200 m	Pr	=	0.2161729	*	**300**	=	**64.85**	watts
200 m	Pr	=	0.2161729	*	**400**	=	**86.47**	watts
200 m	Pr	=	0.2161729	*	**500**	=	**108.09**	watts
200 m	Pr	=	0.2161729	*	**600**	=	**129.70**	watts
200 m	Pr	=	0.2161729	*	**700**	=	**151.32**	watts
200 m	Pr	=	0.2161729	*	**800**	=	**172.94**	watts
200 m	Pr	=	0.2161729	*	**900**	=	**194.56**	watts
200 m	Pr	=	0.2161729	*	**1000**	=	**216.17**	watts
200 m	Pr	=	0.2161729	*	**2000**	=	**432.35**	watts
200 m	Pr	=	0.2161729	*	**3000**	=	**648.52**	watts
200 m	Pr	=	0.2161729	*	**4000**	=	**864.69**	watts
200 m	Pr	=	0.2161729	*	**5000**	=	**1080.86**	watts
200 m	Pr	=	0.2161729	*	**6000**	=	**1297.04**	watts
200 m	Pr	=	0.2161729	*	**7000**	=	**1513.21**	watts
200 m	Pr	=	0.2161729	*	**8000**	=	**1729.38**	watts
200 m	Pr	=	0.2161729	*	**9000**	=	**1945.56**	watts
200 m	Pr	=	0.2161729	*	**10000**	=	**2161.73**	watts

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

Distance	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	=	Pd	*	Ar			
200 m	Pr	=	1.502163	*	**100**	=	**150.22**	watts
200 m	Pr	=	1.502163	*	**200**	=	**300.43**	watts
200 m	Pr	=	1.502163	*	**300**	=	**450.65**	watts
200 m	Pr	=	1.502163	*	**400**	=	**600.87**	watts
200 m	Pr	=	1.502163	*	**500**	=	**751.08**	watts
200 m	Pr	=	1.502163	*	**600**	=	**901.30**	watts
200 m	Pr	=	1.502163	*	**700**	=	**1051.51**	watts
200 m	Pr	=	1.502163	*	**800**	=	**1201.73**	watts
200 m	Pr	=	1.502163	*	**900**	=	**1351.95**	watts
200 m	Pr	=	1.502163	*	**1000**	=	**1502.16**	watts
200 m	Pr	=	1.502163	*	**2000**	=	**3004.33**	watts
200 m	Pr	=	1.502163	*	**3000**	=	**4506.49**	watts
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~**4000**~~	~~=~~	~~**6008.65**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~**5000**~~	~~=~~	~~**7510.82**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~**6000**~~	~~=~~	~~**9012.98**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~**7000**~~	~~=~~	~~**10515.14**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~**8000**~~	~~=~~	~~**12017.30**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~**9000**~~	~~=~~	~~**13519.47**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~**10000**~~	~~=~~	~~**15021.63**~~	~~watts~~

Table 4. Power Received with 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

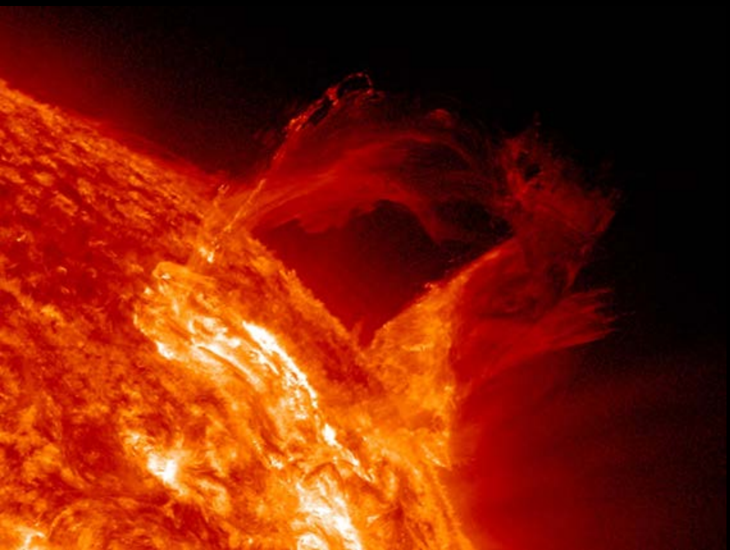
Case 2 frequency = 36.0 GHz ➔ λ = .833 cm

Case 3 frequency = 95.0 GHz ➔ λ = 0.316 cm

Experiment Procedure -1

The proposed experiment has three phases:

- Phase I is ground testbed work,
- Phase II is on-orbit test bed work with minimal augmentation and ISS / interoperating equipment interface requirements, and
- Phase III is on-orbit work with augmentation/optimization as needed to accommodate more extensive ISS / interoperating equipment interface requirements.



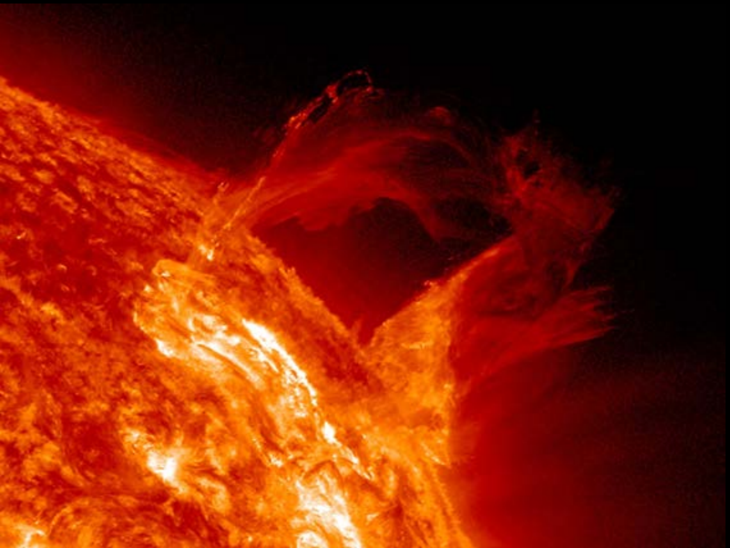
Experiment Procedure - 2

Each Phase will have eight task elements which will be iterated and are intended to leverage the recursive benefit of both the iterations and evolving understanding of customer requirements.

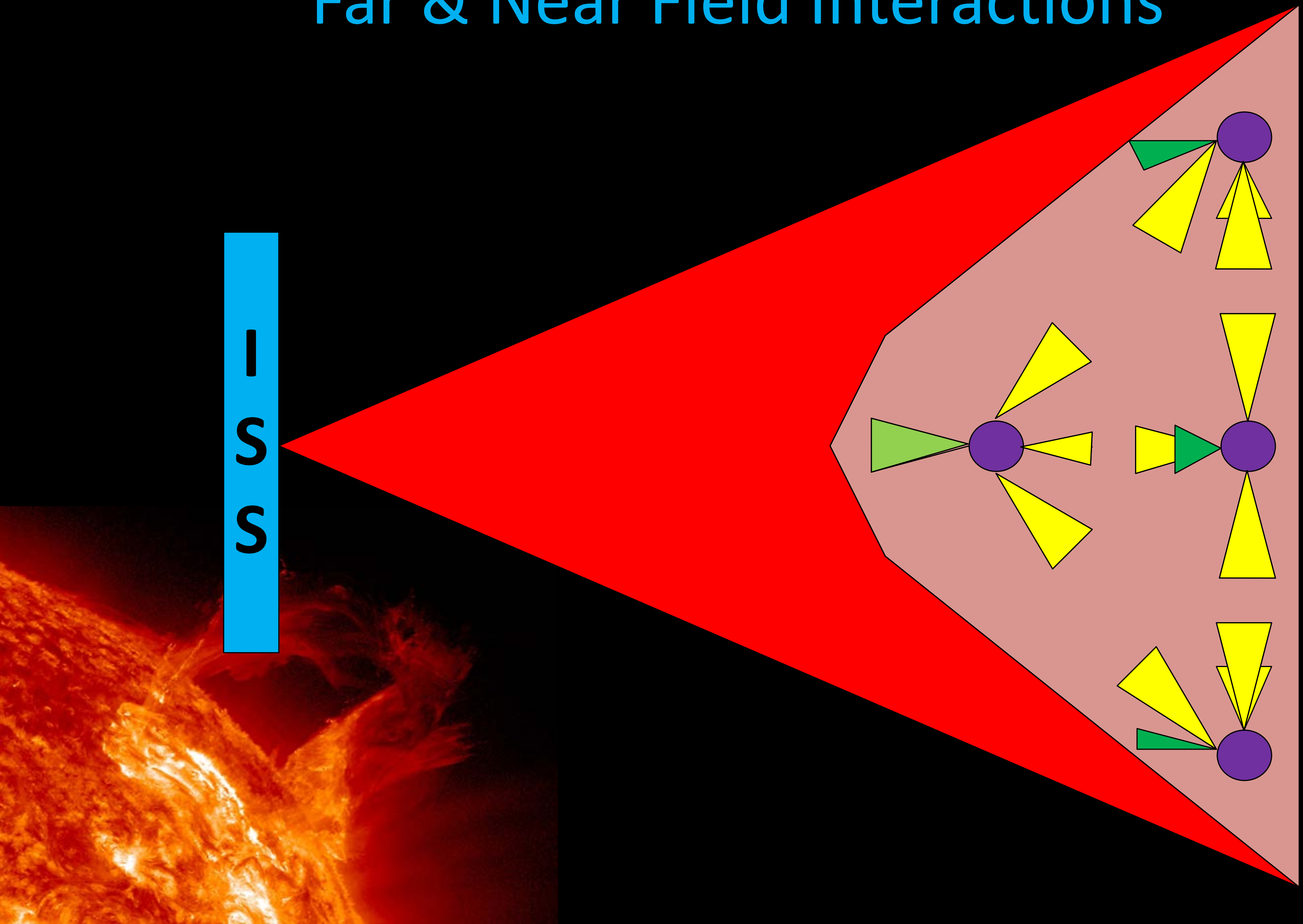
- Task 1 Mission Definition, Planning & Management
- Task 2 Requirements Definition
- Task 3 Interface Definition/Characterization
- Task 4 Testbed Implementation
- Task 5 Application Coding & Hardware Definition
- Task 6 Verification & Validation
- Task 7 Technology Demonstration
- Task 8 Reporting, Presentations, and Identification of Follow-on Work

Tetrahedral Target & Formation

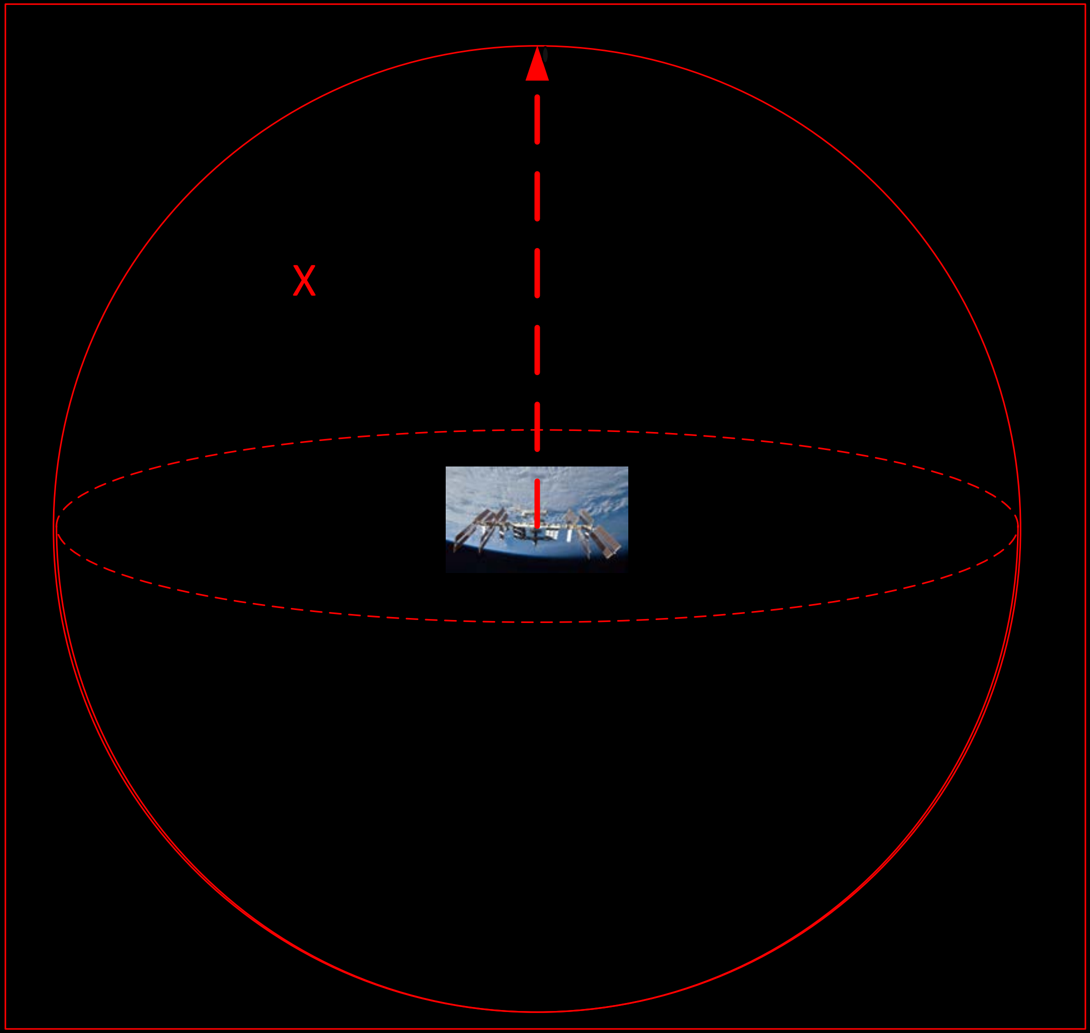
- Tetrahedron – most fundamental locked 3 dimensional structure.
- Allows for fixed local position/orientation.
- Applicable to both individual physical targets and formations.
- Both target and formation scale factors must be experimentally determined based on the sensible combination of far field and near field effects observed.



Beam to Tetrahedral Formation
Far & Near Field Interactions

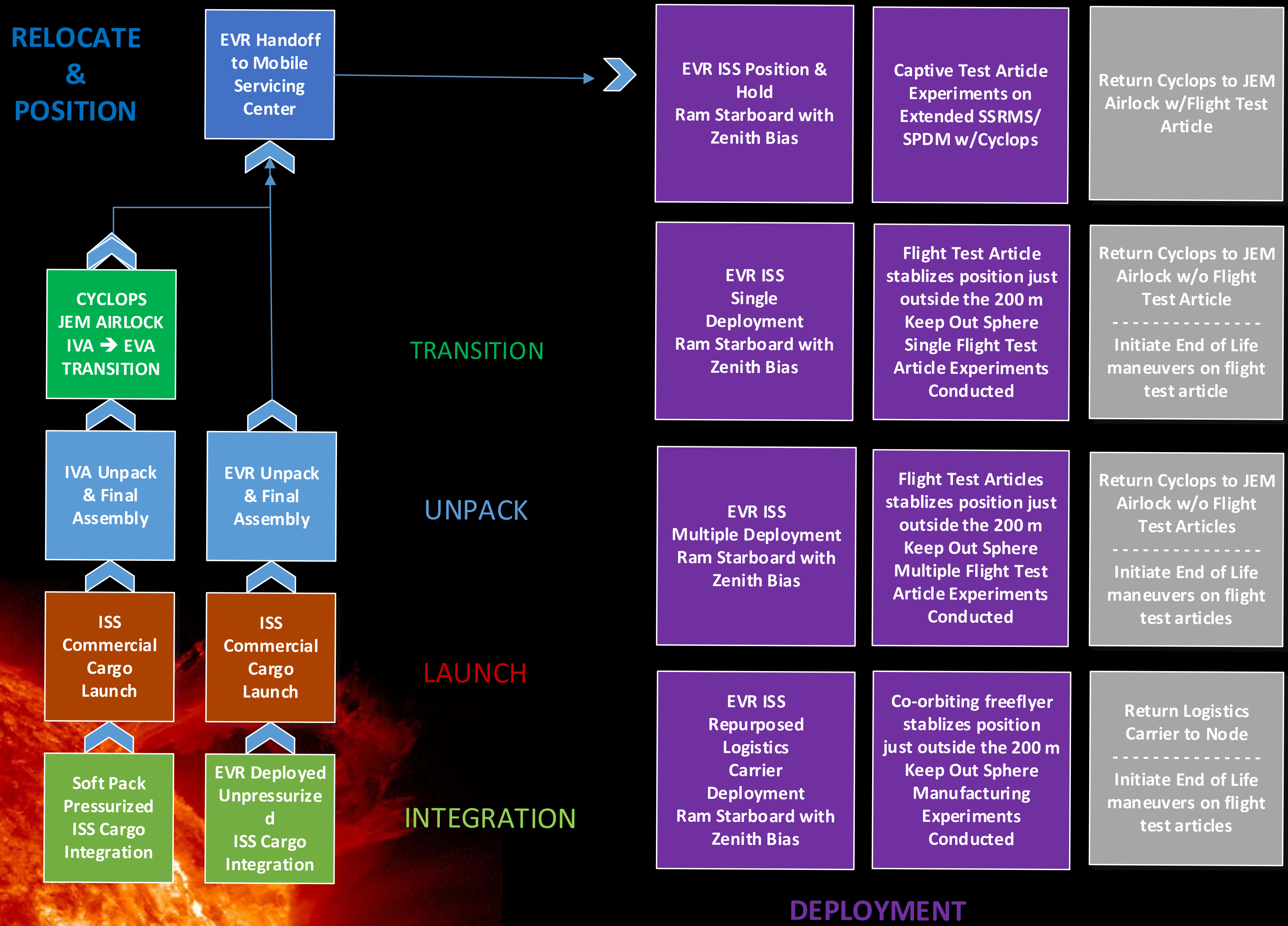


ISS Keep Out Sphere 200 m Radius



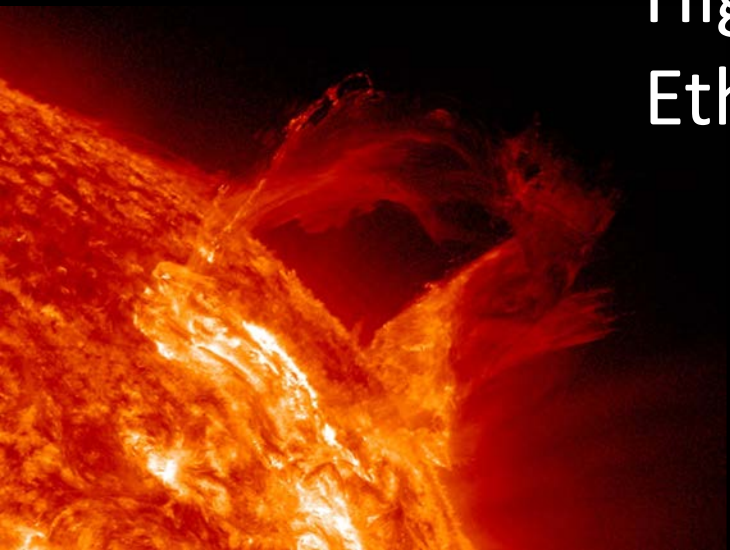
SSPB preferred location for deployed flight test articles is RAM (forward) – Starboard with a Zenith (away from Earth) bias.

SSPB Mission Concept of Operations



JEM Exposed Facility Accommodations

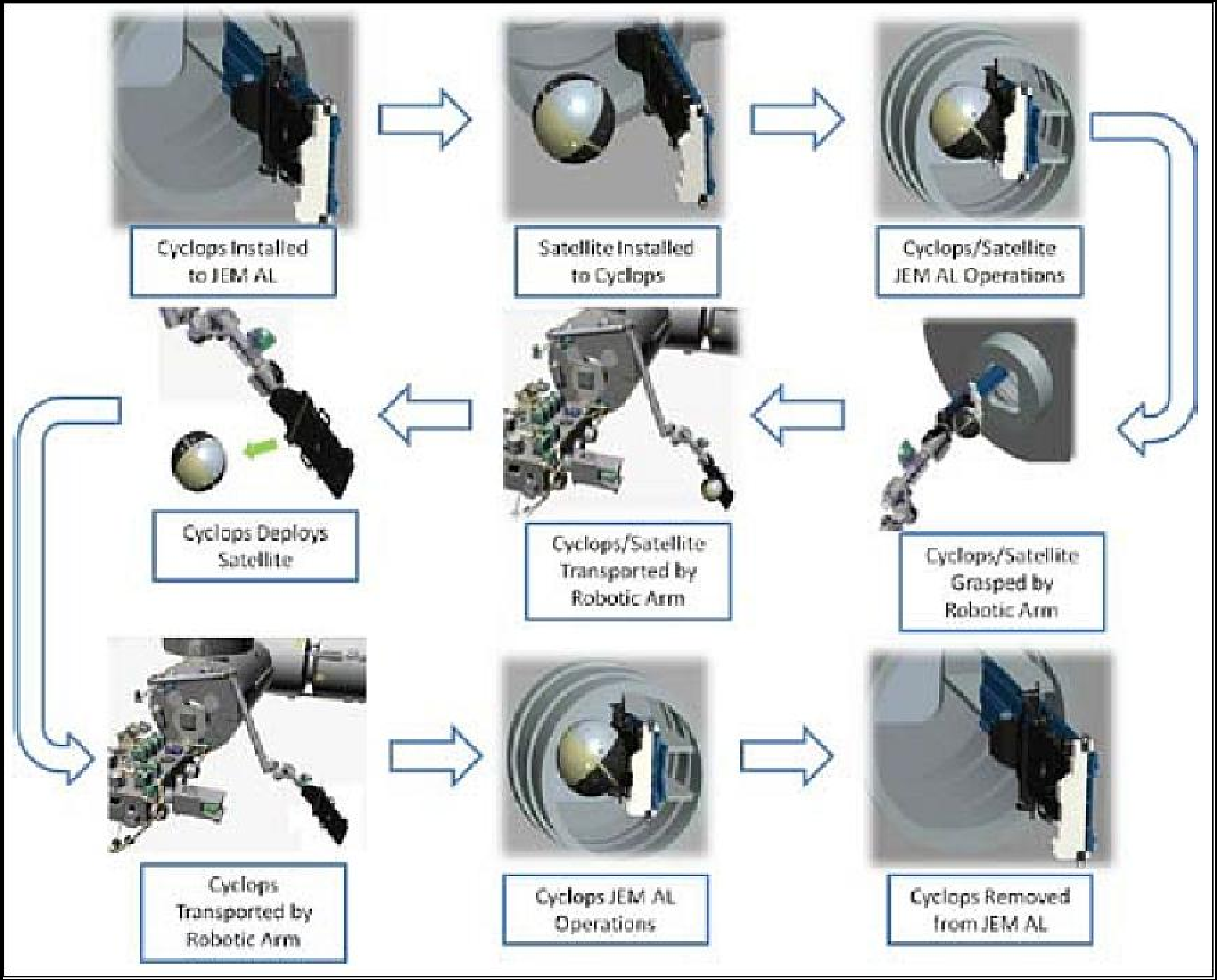
- Mass: 500 kg (10 Standard Sites, mass w/PIU)
- Mass: 2500 kg (3 Heavy Sites, mass w/PIU)
- Volume: 1.5 m3   (1.85m x 1m x 0.8m)
- Power: 3 kW/6 kW, 113-126 VDC
- Thermal: 3 kW/6 kW cooling
- Data: Low Rate: 1 Mbps MIL-STD-1553
  High Rate: 43 Mbps (shared)
  Ethernet: 100Base-TX



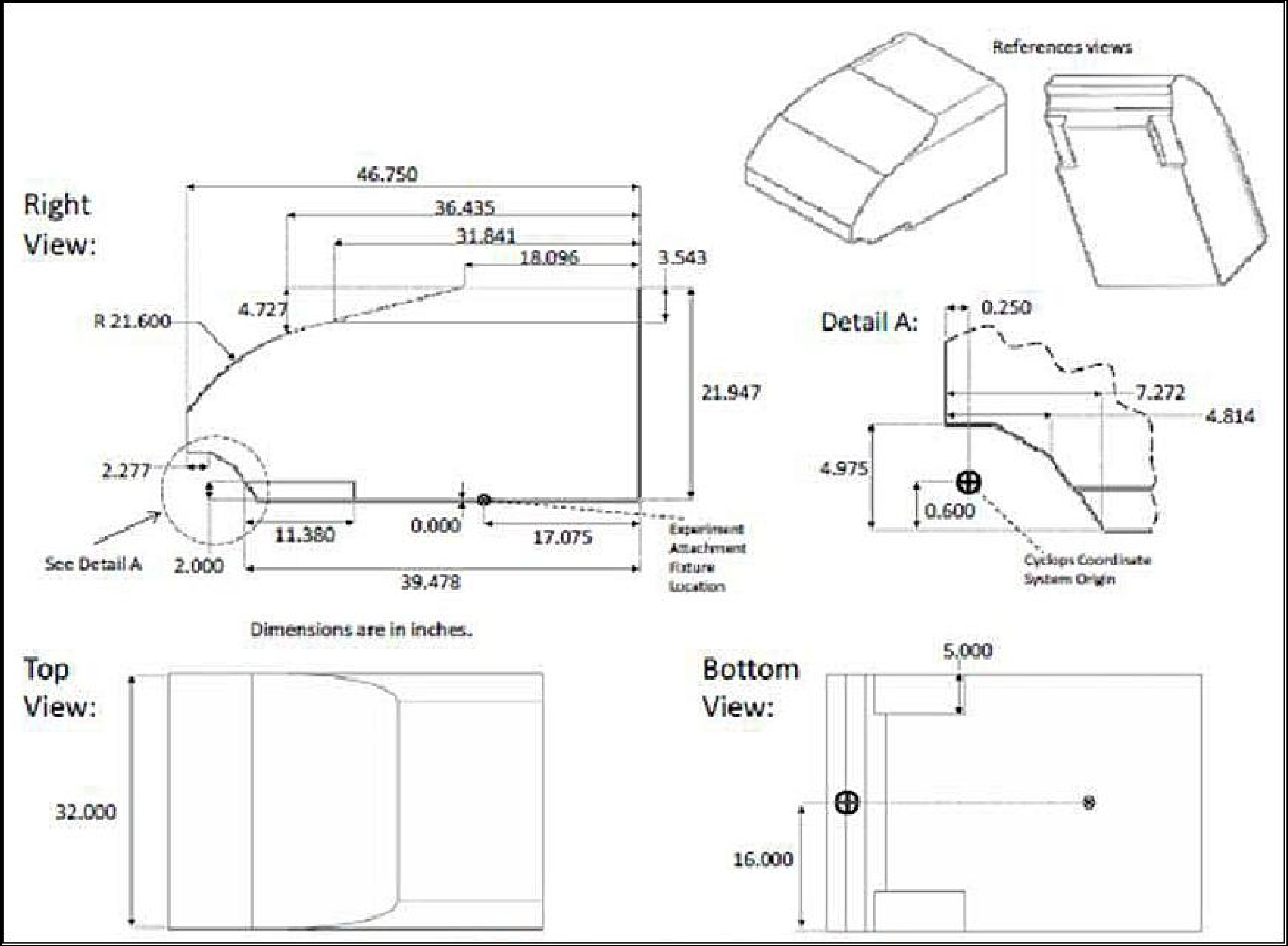
ISS Operational/Safety Considerations

- Soft Pack Launch Considerations
  - Within scope of normal operations
  - Safety requirements well defined
- JEM Airlock/Cyclops/Mobile Servicing Centre Deploy
  - Within scope of normal operations
  - Safety requirements evolving but tractable
- Co-orbiting Outside Space Station Zone of Exclusion
  - Novel extension of normal operations
  - Safety requirements evolving but tractable
- Experiment Operational Modes Leverage Proven Tasks
  - Mobile Servicing Center Held
  - Mobile Servicing Center Deployed (single)
  - Mobile Servicing Center Deployed (formation)
  - Commercial Cargo Carrier Reuse

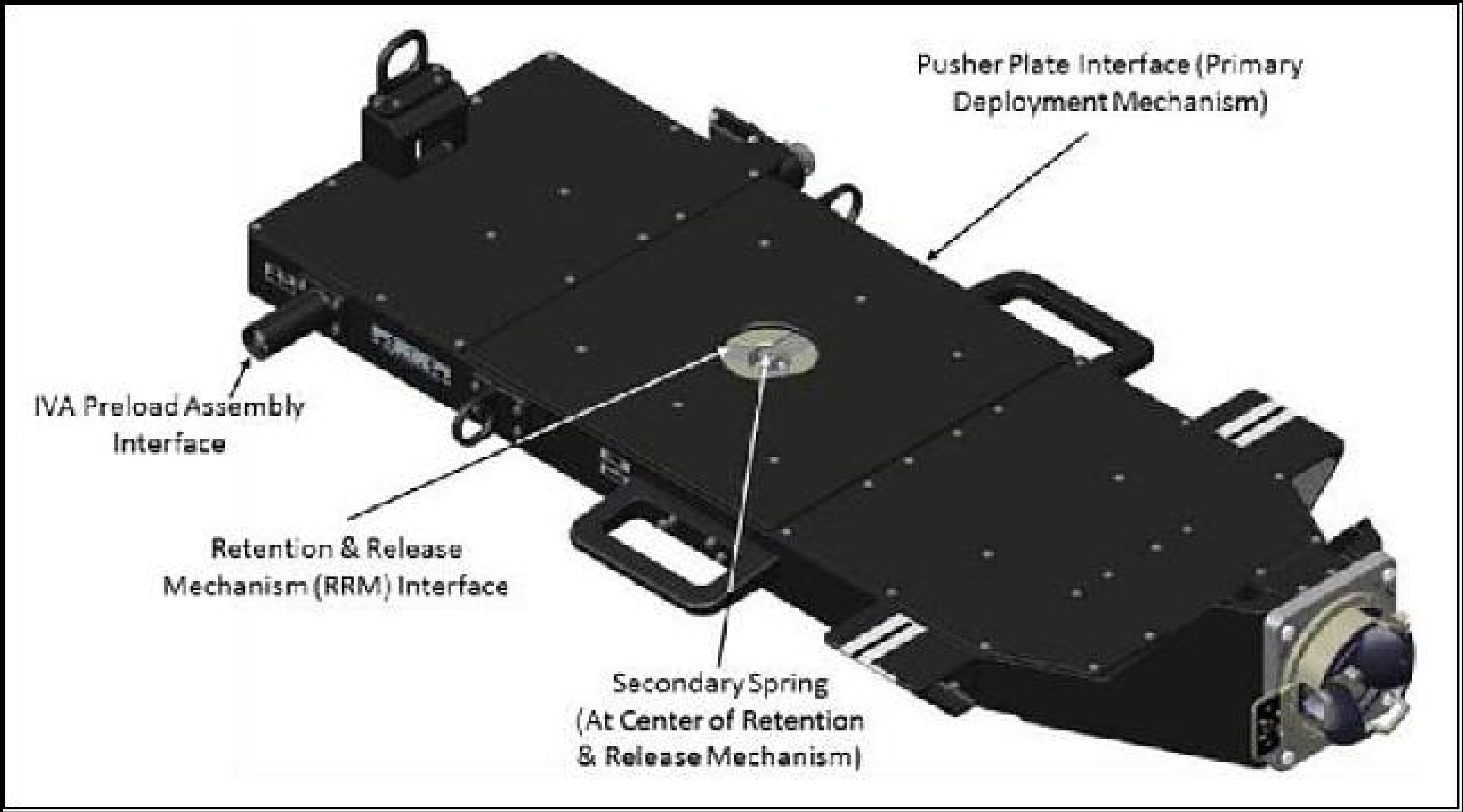
Cyclops Concept of Operations



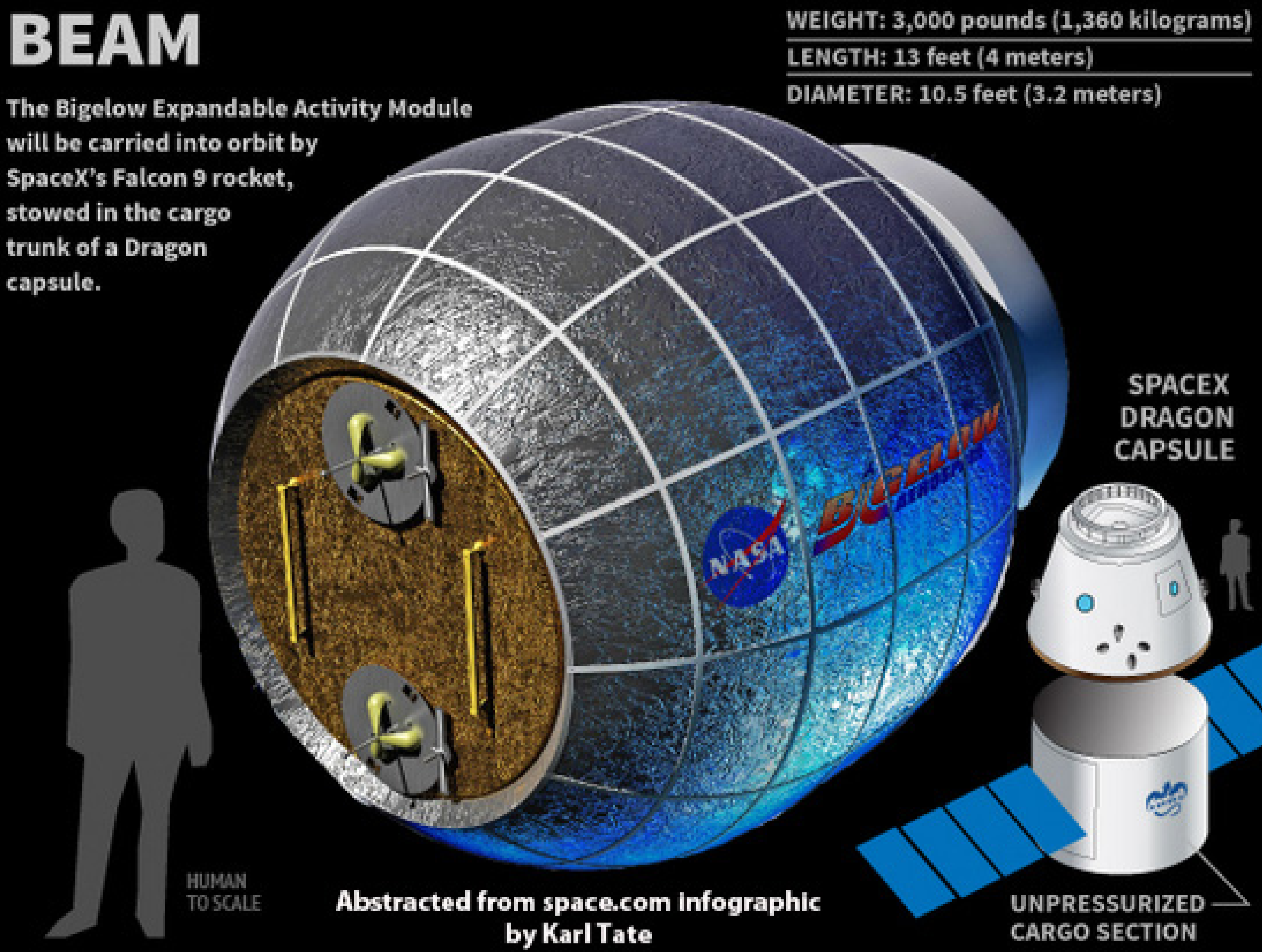
Cyclops JEM Airlock Deployment Volume



Cyclops Deployment Mechanism



NASA BEAM

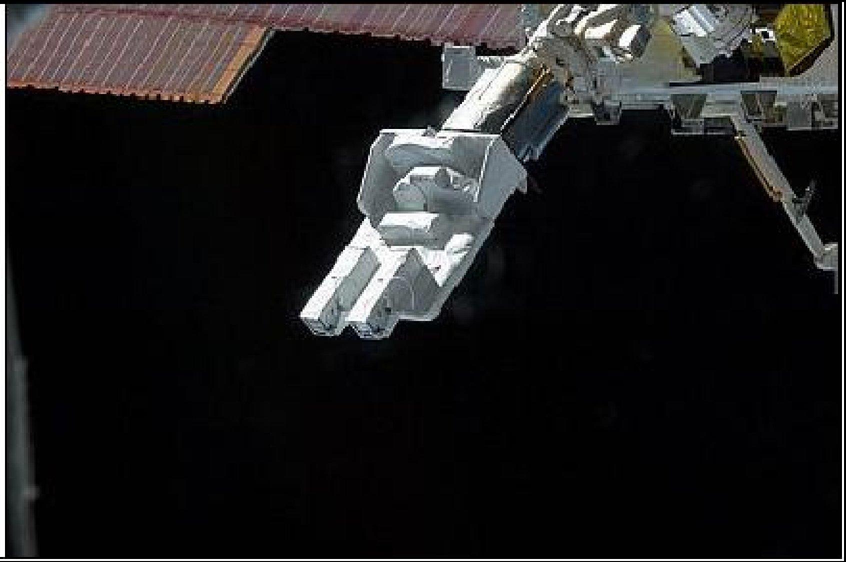


BEAM
The Bigelow Expandable Activity Module will be carried into orbit by SpaceX's Falcon 9 rocket, stowed in the cargo trunk of a Dragon capsule.
WEIGHT: 3,000 pounds (1,360 kilograms)
LENGTH: 13 feet (4 meters)
DIAMETER: 10.5 feet (3.2 meters)
SPACEX DRAGON CAPSULE
HUMAN TO SCALE
UNPRESSURIZED CARGO SECTION
Abstracted from space.com infographic by Karl Tate

Cubesat Considerations

- 1 Unit (U) = 10 cm x 10 cm x 11cm
- Can be 1U, 2U, 3U, or 6U in size
- Raw facing Surface Area of 100 cm^2 per U
- Ability to augment surface area by deployable and/or 3 dimensional antenna structures.
- Typical Power Budget is 12.5 Watts per U
- Minimum power beaming distance to deliver usable power must exceed the ISS zone of exclusion.
- Ability to reach a given target may be subject to structural occlusion and operations timing/sequencing considerations.

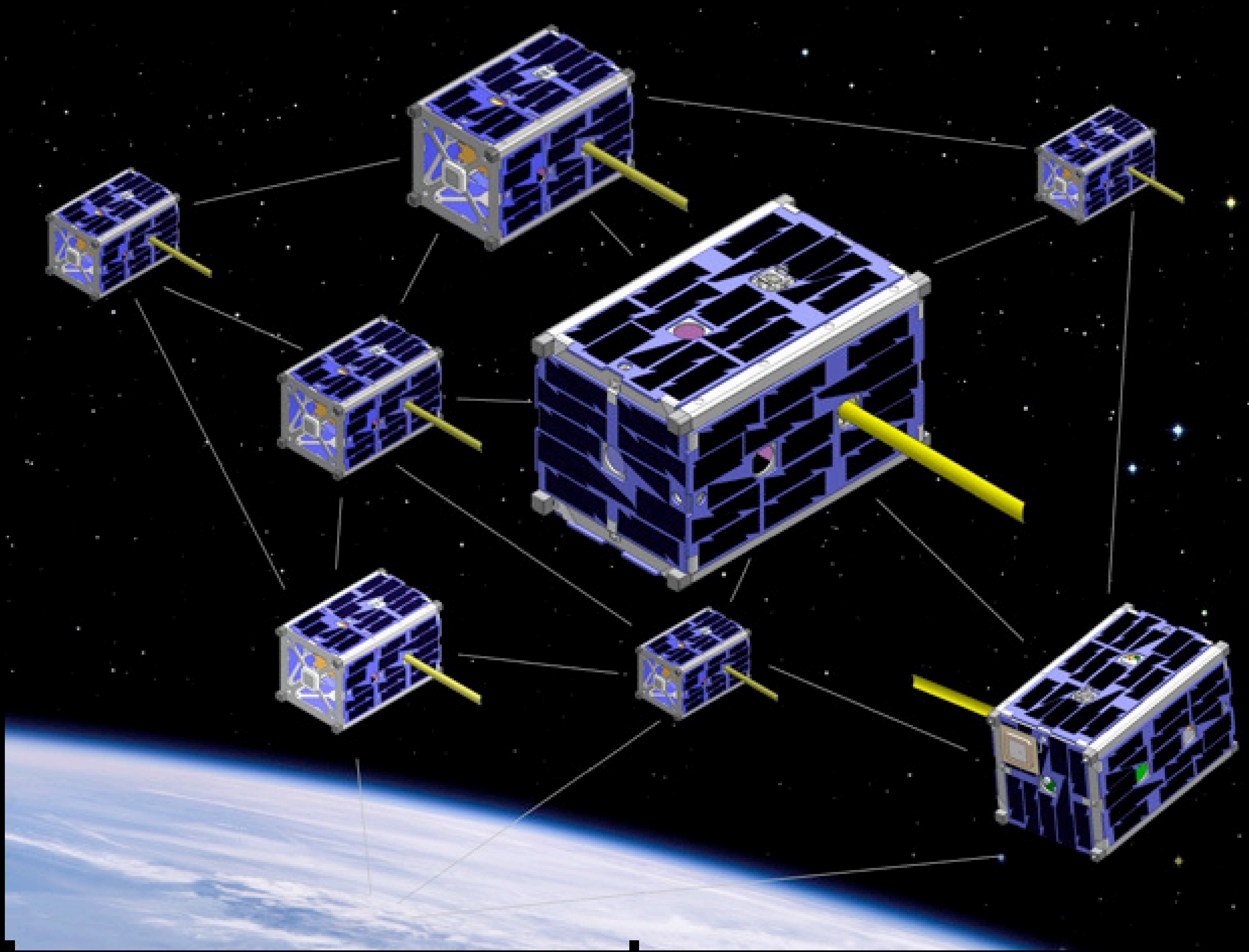
JEM Airlock & CubeSat Launcher



Possible Architectures – Cubesat Swarm

- All three test cases applicable
  - Reduction in complexity
  - Reduction in mass and/or volume
  - Provide delta V
- Multiple unpressurized and pressurized launch opportunities
  - Logistics Carrier Deployment
  - JAXA JEM Kibo Back-Porch launch & retrieve
  - Express Payload Rack launch & retrieve
- Consumable as well as repeatable low cost experiments
- Potential for 3-D printing experiment optimization
- Lowest cost flight opportunities that support rapid prototyping
  - Leverage STEM as a “maker” project

Notional Cubesat Swarm



JAXA Kibo robotic arm deploying cubesats

Possible Architectures – ExoSpheres Tool Kit

- All three test cases applicable
  - Reduction in complexity
  - Reduction in mass and/or volume
  - Provide delta V

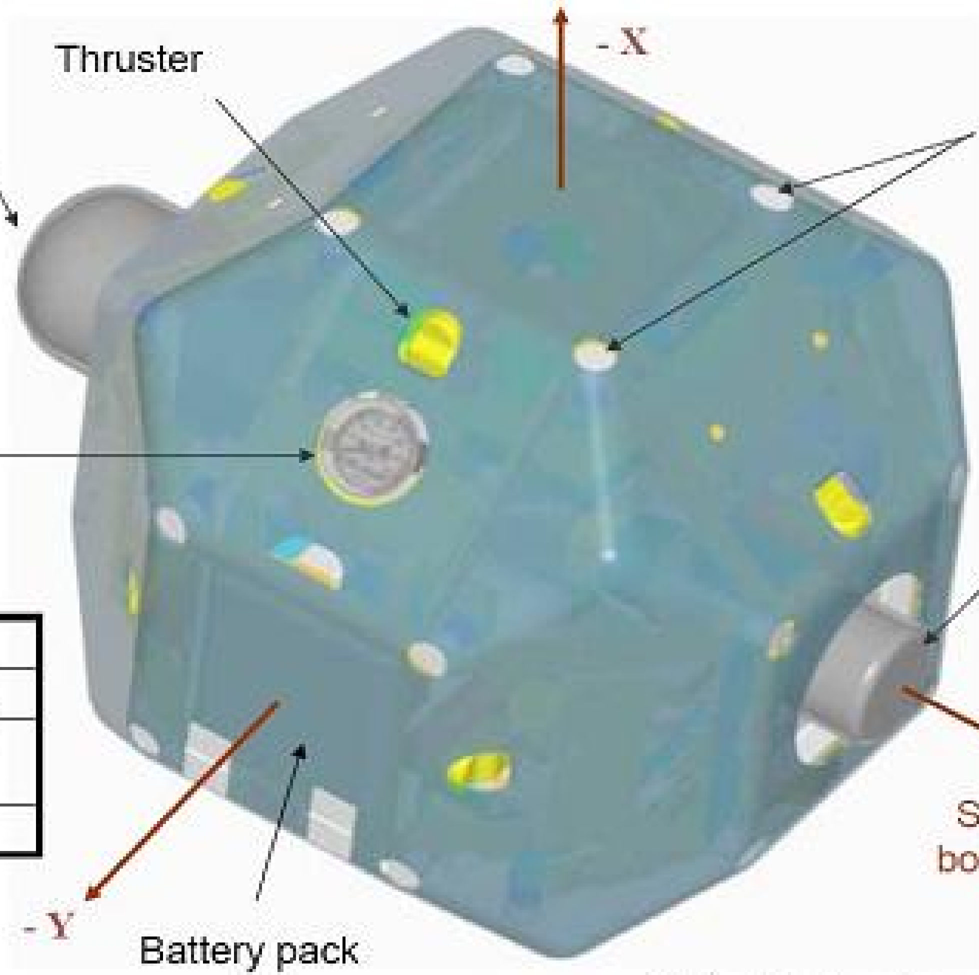
- Multiple unpressurized and pressurized launch opportunities
  - JAXA Kobe Back-Porch launch & retrieve
  - Express Payload Rack launch & retrieve

- Reusable element of EVA Robotics Tool Kit

- Experiment as infrastructure proof of concept

SPHERES

SPHERES Satellite



Diameter	0.2 m (8 in.)
Mass	4.4 kg (9.68 lbs)
Thrust (single thruster)	<0.1 N (35 psi)
CO_2 Capacity	172 g (6 oz.)

Payload Systems Inc

23

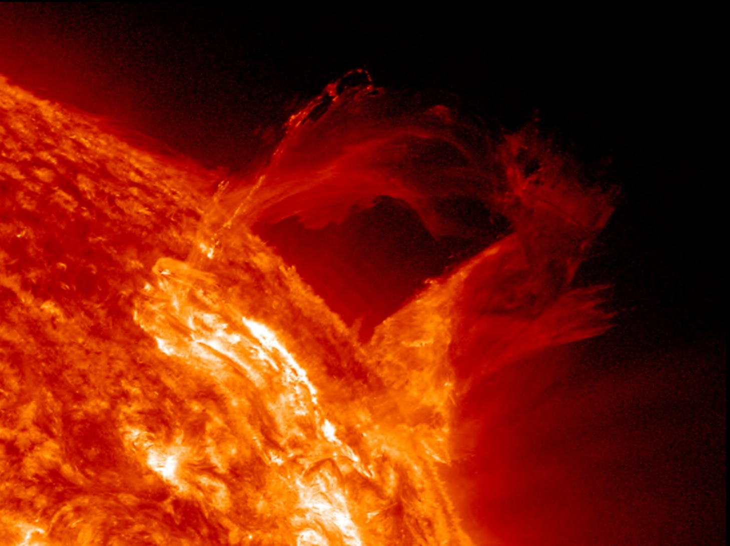
Possible Architectures – Spacecraft as Infrastructure

- All three test cases applicable
  - Reduction in complexity
  - Reduction in mass and/or volume
  - Provide delta V
- Supports loosely coupled systems of systems approach
- Beaming (power, data, force, heat) as:
  - external inputs/outputs that change with mission segment
  - internal managed interfaces
- Plug-in/Plug-out technology and interface management
- Infrastructure Concepts
  - LEO/MEO/GEO “Telco” central office(s)
  - Cis-lunar shared use relay / operations support platforms
    - L1/L2/L4/L5 or other lunar Halo Orbits
    - Can transform lunar operations to 24x7

Reality Check

- Reducing the number of perceived “impossible things that have to be accepted before breakfast”* is a way of incrementally disabusing people of unfounded notions.

- Doing something real with the technology that is of demonstrable value can help to establish the confluence of interests necessary to mature the technology for more advanced applications.



* Allusion to “Alice in Wonderland” by Lewis Carroll. "Alice laughed: "There's no use trying," she said; "one can't believe impossible things."
"I daresay you haven't had much practice," said the Queen. "When I was younger, I always did it for half an hour a day. Why, sometimes I've believed as many as six impossible things before breakfast."

Why does this matter? - Reduction in Complexity

- The postulate is that unbundling power systems can significantly reduce the design, integration, operations, maintenance, enhancement, and/or evolution challenges for a spacecraft.

- As we transition from building one-off spacecraft to *enduring infrastructure* managing the cost , schedule, and technical risk of each of these aspects of a program becomes ever more critical.

Why does this matter? - Reduce Mass and/or Volume

- The mass and volume associated with the power system of a spacecraft is a material fraction of the overall budgets for the spacecraft.

- A material reduction can facilitate doing more with less.
  - More frequent and varied flight opportunities,
  - going further and/or going faster,
  - more resources/experiments/capabilities

Why does this matter? Provide Additional delta-V

- The ability to optimize a power system of a spacecraft to provide an additional change in velocity at opportune moments can materially alter the operational constraints on a spacecraft.

- Additional delta-V can facilitate doing more with less.
    - More frequent and varied flight opportunities,
    - going further and/or going faster,
    - more resources/experiments/capabilities

Phase I – Ground Testbed Work

Define and implement/prototype a scalable parametric model for unbundled power systems for sustained free-flyer operations extensible to propulsion, surface, and/or infrastructure operations.

Exercise the model to demonstrate:

- an understanding of the trade space,
- any interactions between and with unbundled power system elements, both in terms of what is known and what is known to be unknown,
- unbundled power system element specifications, as well as
- a characterization of all required interfaces.

Demonstrate and test experiment as a mixed mode simulation using the ground with increasing fidelity to both validate the parametric model and all required physical interfaces for Phase II & III work.

Phase II - On-orbit Work (Functional Test)

We propose to use an on orbit Ka Band transmitter, driven at it's maximum power rating starting with a standard Ka Band communications wave form from the available library.

The transmitter will be programmed to generate a uniform characterizable beam that can be actively pointed at defined testing targets located some distance from the station for various defined periods of time.

Resource availability permitting the library of alternate wave forms will be tested to determine measurable variability in performance.

The objective is to provide some level of augmented power, communications, and attitude control/positioning services. The anticipated targets are ISS and/or cooperating vehicle launched cubesats.

This combination of equipment allows for power transmission, communications, far field/near field effect analysis and management, test of system element interactions (separately and as a system), formation flying/alignment, and various propulsion approaches to be tested and used to the benefit of multiple experiments.

Phase III - On-orbit work with Augmentation / Optimization (Expand Performance Envelope)

We propose to use one or more on orbit Ka Band and/or W band transmitters, driven at their maximum power rating and optimized wave forms to provide augmented power, communications, and some level of attitude control/positioning services to one or more co-orbiting cooperating spacecraft/elements (e.g., BEAM, Dragon, Cygnus, Progress, etc.).

The transmitter will be programmed to generate a uniform characterizable beam that can be actively pointed at the appropriately augmented spacecraft/elements while located some distance from the station for various defined periods of time and on a priority override basis during ingress or egress from the ISS sphere of exclusion.

This combination of equipment allows for a different scale of power transmission, far field/near field effect analysis and management, formation flying/alignment, and various propulsion approaches to be tested and used to the benefit of multiple experiments.

It is anticipated that this combination of equipment could be repurposed as crew-tended free-flyers for extended duration micro-g/production manufacturing cell runs and other activities.

What is the Proposed Solution - 1

- Space-to-space power beaming is an application of Space Solar Power technology which could be tested/implemented now to immediate benefit as well as serve as a means of incrementally maturing the technology base.
- XISP-Inc has brought together a truly innovative partnership of interest parties to accomplish technology development work in this area including both government, commercial, university, and non-profit sectors. Many formal letters of interest have been submitted to NASA and/or XISP-Inc and are available on request.

What is the Proposed Solution - 2

- This mission starts with the design and implement/prototype a parametric model for unbundled power systems for spacecraft propulsion and/or sustained free flyer/surface operations in conjunction with the NASA ARC Mission Control Technologies Laboratory and other interested parties.
- The opportunity to craft viable technology demonstrations will establish the basis for a confluence of interest between real mission users and the technology development effort.
- This could lead to a range of technology development missions on the ISS and subsequent fight opportunities that can make efficient and effective use of beamed energy for propulsion and/or sustained operations.
- This has come to pass and there is now a concerted effort to move forward with mission development.

What is the Proposed Solution - 3

- Several potential research opportunities have emerged that could make use of a combination of resources currently available or that can be readily added to ISS:
- Of particular interest is the use of one or more of the available Ka band (27 to 40 Ghz) communications transmitters on ISS as well as the potential for adding one or more optimized W band transmitters (75 to 110 GHz).
- The use of simplified delivery to ISS of enhance equipment and/or flight test articles as soft pack cargo from Earth, the Japanese Kibo laboratory airlock to transition flight systems to the EVA environment, the Mobile Servicing Center for ram-starboard deployment positioning with a zenith bias, and simplified deployment mechanisms can serve as a useful first step toward demonstrating an ability of ISS to support co-orbiting freeflyer spacecraft systems.

What is the Proposed Solution - 4

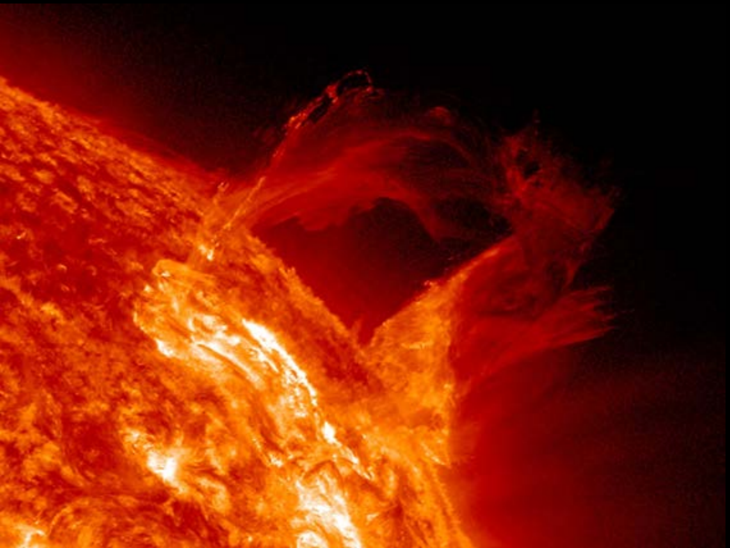
- This combination of equipment allows for power transmission, far field/near field effect analysis and management, formation flying/alignment, and various propulsion approaches to be tested and used to the benefit of multiple experiments; as well as provide augmented power, communications, and some level of attitude control/positioning services to a co-orbiting free-flyers and/or other elements (e.g., BEAM, Dragon, Cygnus, etc.).
- This combination of equipment could be repurposed as crew-tended free-flyers for some number of extended duration micro-g/production manufacturing cell runs.
- Also, commercial space applications include mission enhancements, expansion of operational mission time, and out-bound orbital trajectory insertion propulsion.

Possible Architectures – Co-orbiting Free-Flyers

- All three test cases applicable
  - Reduction in complexity
  - Reduction in mass and/or volume
  - Provide delta V
- Repurposing logistics craft as hosts for crew tended manufacturing cells
  - Commercial Cargo (Space-X, Orbital)
  - International Cargo Carriers (as applicable)
- Commercial Opportunity for optimized co-orbiting free-flyers
  - NASA Bigelow Expandable Activity Module (BEAM)

Crew Tended Free Flyer Considerations

- Minimum power beaming distance to deliver usable power must exceed the ISS zone of exclusion
- Ability to augment rectenna surface area by deployable and/or 3 dimensional antenna structures may be required.
- Ability to reach a given target may be subject to structural occlusion and operations timing/sequencing considerations.



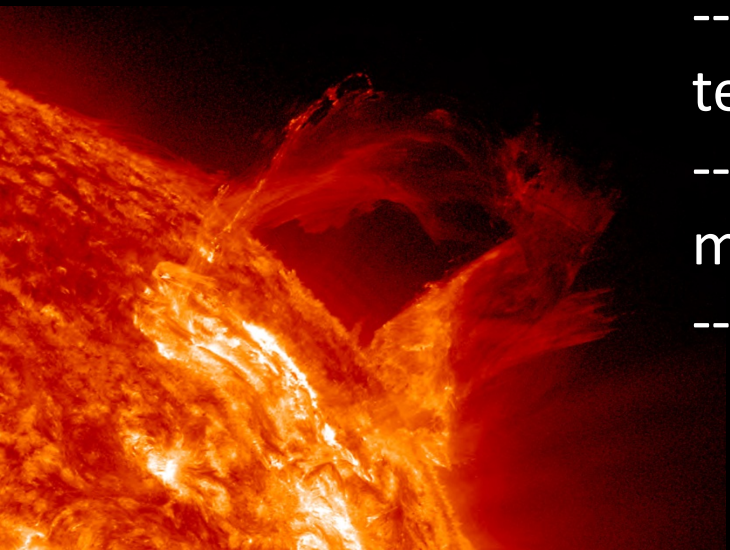
Power System Trade Space - Taxonomy

- Spacecraft survival is dependent on the power system functioning in almost all cases.
- Any innovation must be understandable in the context of the known trade space and cross discipline accessible or it will not fly.
- The innovation must either:

  -- Reduce cost, schedule, and/or technical risk;

  -- Demonstrably enhance the mission; or

  -- Enable the mission



Why Solve the Problem?

➔Reducing cost, schedule & technical risk

➔Mission enhancing technology

➔Mission enabling technology