SPACE-TO-SPACE POWER BEAMING A COMMERCIAL MISSION TO UNBUNDLE SPACE POWER SYSTEMS TO FOSTER SPACE APPLICATIONS

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Outline

- The Problem
- Why Solve the Problem?
- The Potential Impacts . . .
- Relevance to NASA & Others . . .
- What are we unbundling?
- Experiment Outline (Objectives, Description, Work Vectors)
- Technological Challenges
- Our Team Circa Today
- Next Steps
- Conclusion
- Backup Slides (intended for offline discussion only)

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
- reduce spacecraft mass and/or volume
- reallocate spacecraft mass and/or volume
- impart additional delta-V to a spacecraft

Why Solve the Problem?

➔Reducing cost, schedule & technical risk

➔Mission enhancing technology

➔Mission enabling technology

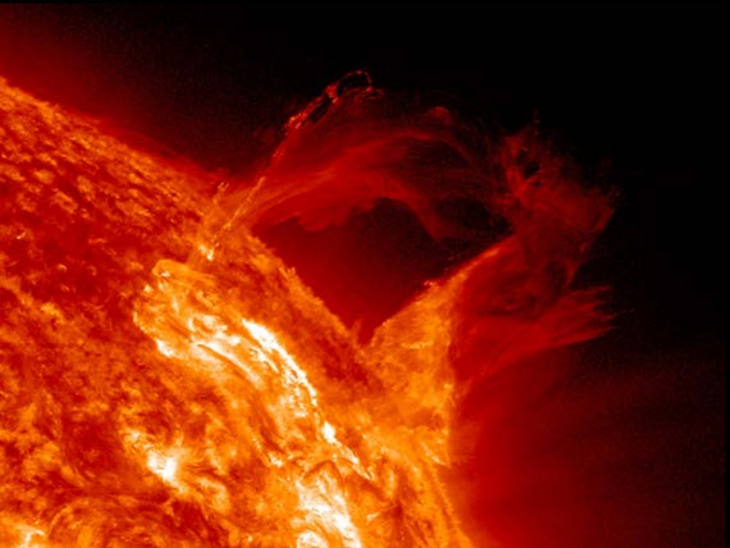
The Potential Impacts . . .

- 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

Space-to-space power beaming is an application of space solar power technology which could:

1. be tested/implemented now to immediate benefit, and
2. serve as a means of incrementally maturing the technology base.



Relevance to NASA & Others - 2

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

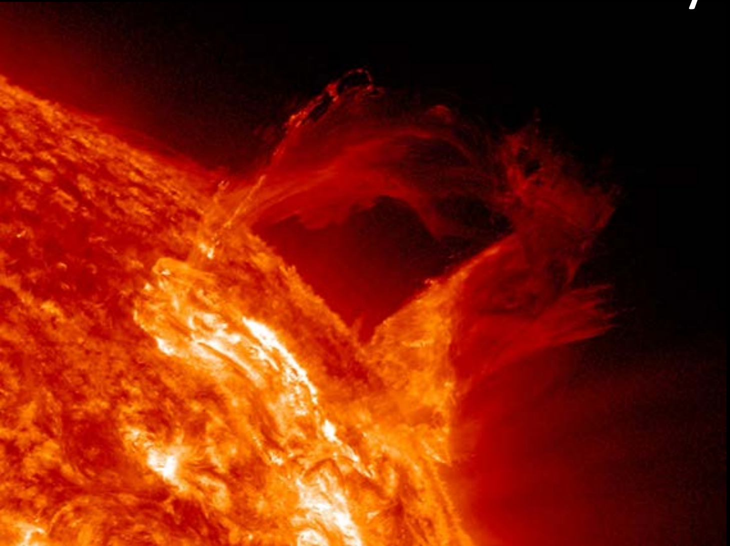
1. leverages available ISS resources to serve as a testbed,
2. simultaneously supports payload experiments, and
3. serves to help mitigate perceived cost, schedule, and technical risk associated with the use of Space Solar Power.

Relevance to NASA & Others - 4

- This work is germane to multiple Space Act Agreements being negotiated with various NASA centers an overarching Space Act Umbrella Agreement under negotiation between NASA Headquarters and XISP-Inc.
- The XISP-Inc proposed cubesat target demonstrating power beaming from ISS will require the cooperation of several elements of NASA and Industry, but would result in near term demonstration of space-to-space power beaming, and allow rapid iteration of designs and experiments.

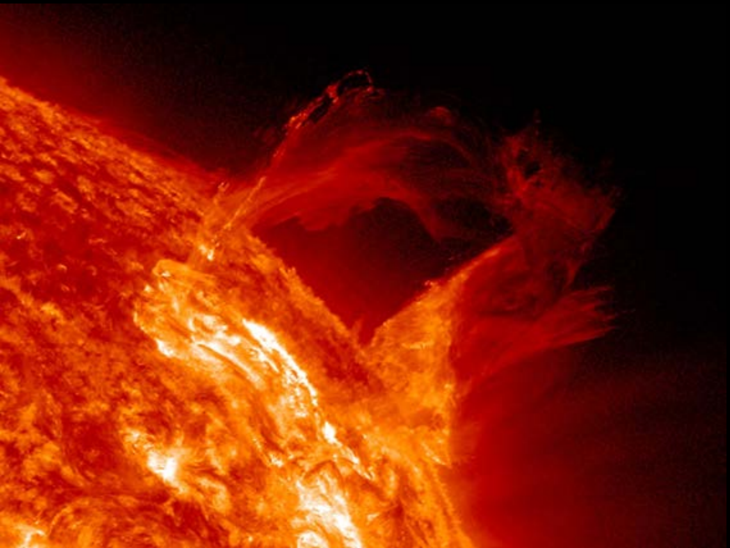
Relevance to NASA & Others - 5

- 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, as well as designs for distributed payloads and sensors for deep space missions including lunar and asteroidal assay work.



Relevance to NASA & Others - 7

- A primary mission of XISP-Inc is to develop cooperative arrangements with different parts of NASA and different industry partners.
- The early implementation of a power beam demonstration on ISS, coordinated by XISP-Inc, could enhance and enable the demonstration of other power beaming designs.



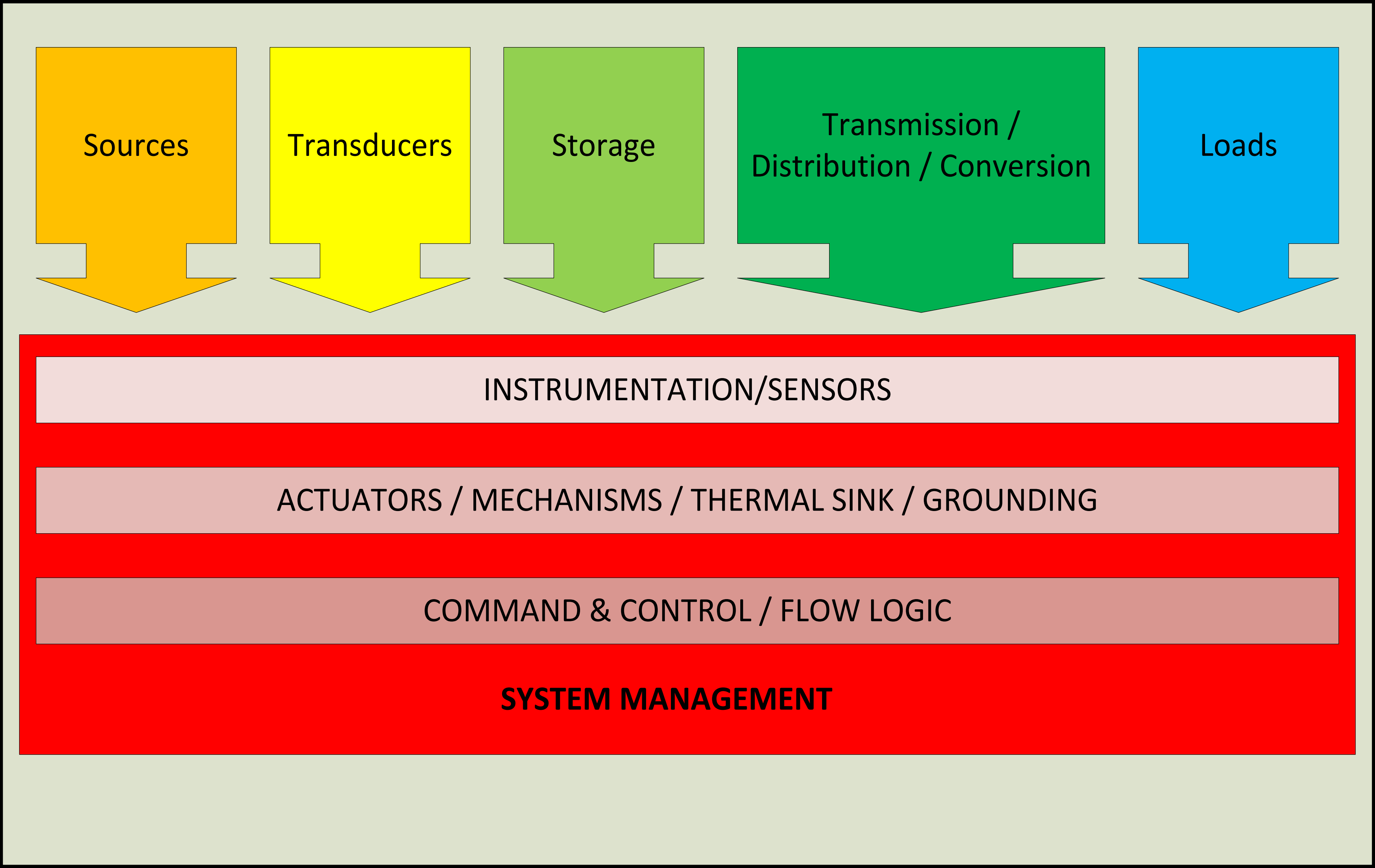
What are we unbundling?

- The intention of the block diagram is to provide 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 multiple co-orbiting spacecraft initially using one or more International Space Station (ISS) based Ka-band transmitters.

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

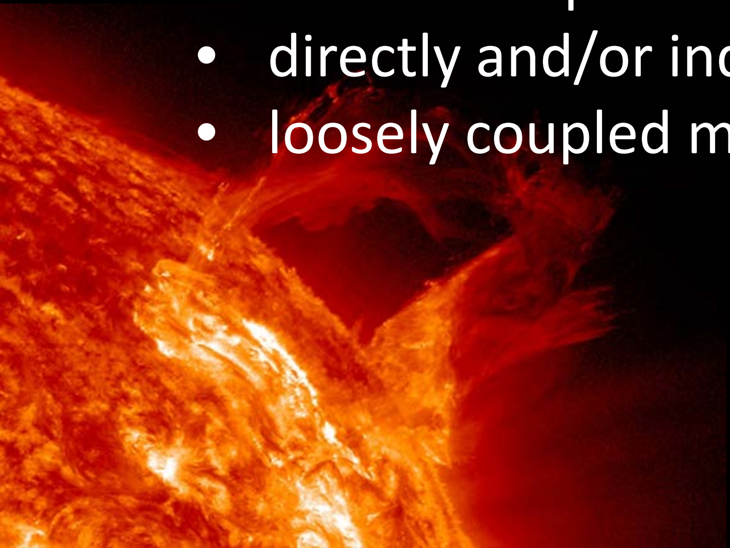
(3) Reduce the cost, schedule, and technical risk associated with the use of the space solar power technology to better address the mission challenges for a new spacecraft and/or infrastructure.

Experiment Description

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.

This can lead to a range of technology development missions on ISS and subsequent flight opportunities that can make efficient and effective use of beamed energy to support:

- sustained operations,
- directly and/or indirectly augmented propulsion, and
- loosely coupled modular structures.



Experiment Work Vectors

(1) Deep Space Industries will provide initial flight test articles in return for testing to their asteroid assay requirements.

(2) NASA ARC Mission Control Technologies (MCL) 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.

Mathematics of Power Beaming* - Power Density

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

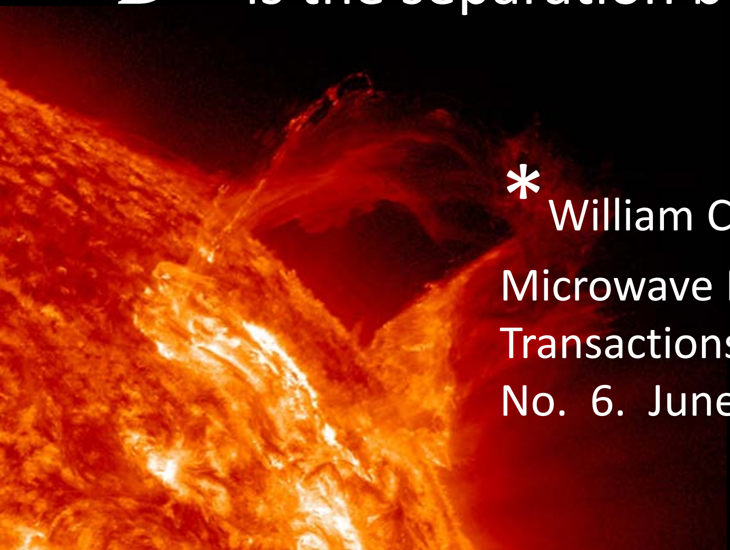
p_d is the power density at the center of the receiving location

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

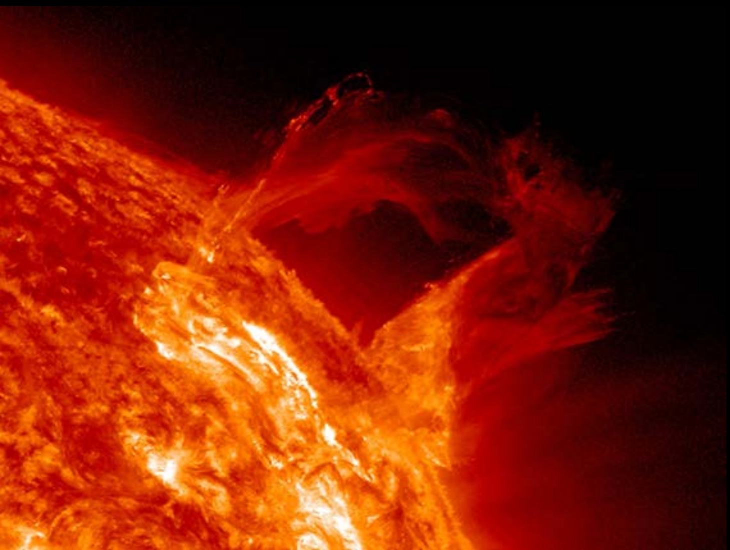
D^2 is the separation between the apertures squared



* 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	Pd	=	Ai	Pi	/	λ**2	D	D		Pd	Ai	Pi	λ**2
	(watts/cm**2)		(cm**2)	(watts)		(cm**2)	(cm)	(cm)		(watts/cm**2)	Source	Source	Source
10 km	Pd	=	1641.732	3000	/	0.693889	1000000	1000000	=	7.09796E-06	STB	ELC/KEF	Ka-Target
1 km	Pd	=	1641.732	3000	/	0.693889	100000	100000	=	0.000709796	STB	ELC/KEF	Ka-Target
200 m	Pd	=	1641.732	3000	/	0.693889	20000	20000	=	0.017744901	STB	ELC/KEF	Ka-Target
1 m	Pd	=	1641.732	3000	/	0.693889	100	100	=	NEAR FIELD	STB	ELC/KEF	Ka-Target
CASE 2	Pd	=	Ai	Pi	/	λ**2	D	D		Pd	Ai	Pi	λ**2
	(watts/cm**2)		(cm**2)	(watts)		(cm**2)	(cm)	(cm)		(watts/cm**2)	Source	Source	Source
10 km	Pd	=	1641.732	3000	/	0.099856	1000000	1000000	=	4.9323E-05	STB	ELC/KEF	W-Target
1 km	Pd	=	1641.732	3000	/	0.099856	100000	100000	=	0.004932299	STB	ELC/KEF	W-Target
200 m	Pd	=	1641.732	3000	/	0.099856	20000	20000	=	0.12330748	STB	ELC/KEF	W-Target
1 m	Pd	=	1641.732	3000	/	0.099856	100	100	=	NEAR FIELD	STB	ELC/KEF	W-Target



*CASE 1 - Express Logistics Carrier/Kibo Exposed Facility (ELC/KEF) Mounted Ka Band Transmitter, 18” Diameter Aperture, 3000 Watts output power, 36 GHz

CASE 2 - ELC/KEF Mounted W Band Transmitter, 18” Diameter Aperture, 3000 Watts output power, 95 GHz

Power Received - More Optimal Solutions

CASE 1* - Anticipated Power Received for various rectenna areas									CASE 2** - Anticipated Power Received for various rectenna areas								
Distance	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received		Distance	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	=	Pd	*	Ar					Pr	=	Pd	*	Ar			
200 m	Pr	=	0.017744901	*	100	=	1.77	watts	200 m	Pr	=	0.12330748	*	100	=	12.33	watts
200 m	Pr	=	0.017744901	*	200	=	3.55	watts	200 m	Pr	=	0.12330748	*	200	=	24.66	watts
200 m	Pr	=	0.017744901	*	300	=	5.32	watts	200 m	Pr	=	0.12330748	*	300	=	36.99	watts
200 m	Pr	=	0.017744901	*	400	=	7.10	watts	200 m	Pr	=	0.12330748	*	400	=	49.32	watts
200 m	Pr	=	0.017744901	*	500	=	8.87	watts	200 m	Pr	=	0.12330748	*	500	=	61.65	watts
200 m	Pr	=	0.017744901	*	600	=	10.65	watts	200 m	Pr	=	0.12330748	*	600	=	73.98	watts
200 m	Pr	=	0.017744901	*	1000	=	17.74	watts	200 m	Pr	=	0.12330748	*	1000	=	123.31	watts
200 m	Pr	=	0.017744901	*	4000	=	70.98	watts	200 m	Pr	=	0.12330748	*	4000	=	493.23	watts
200 m	Pr	=	0.017744901	*	5000	=	88.72	watts	200 m	Pr	=	0.12330748	*	5000	=	616.54	watts
200 m	Pr	=	0.017744901	*	6000	=	106.47	watts	200 m	Pr	=	0.12330748	*	6000	=	739.84	watts
200 m	Pr	=	0.017744901	*	6219	=	110.36	watts	200 m	Pr	=	0.12330748	*	6219	=	766.85	watts
200 m	Pr	=	0.017744901	*	7000	=	124.21	watts	200 m	Pr	=	0.12330748	*	7000	=	863.15	watts
200 m	Pr	=	0.017744901	*	7500	=	133.09	watts	200 m	Pr	=	0.12330748	*	7500	=	924.81	watts
200 m	Pr	=	0.017744901	*	8000	=	141.96	watts	200 m	Pr	=	0.12330748	*	8000	=	986.46	watts
200 m	Pr	=	0.017744901	*	9000	=	159.70	watts	200 m	Pr	=	0.12330748	*	9000	=	1109.77	watts
200 m	Pr	=	0.017744901	*	10000	=	177.45	watts	200 m	Pr	=	0.12330748	*	10000	=	1233.07	watts

- * Express Logistics Carrier/Kibo Exposed Facility (ELC/KEF) Mounted Ka Band Transmitter, 18” Diameter Aperture, 3000 Watts output power, 36 GHz
- ** ELC/KEF Mounted W Band Transmitter, 18” Diameter Aperture, 3000 Watts output power, 95 GHz

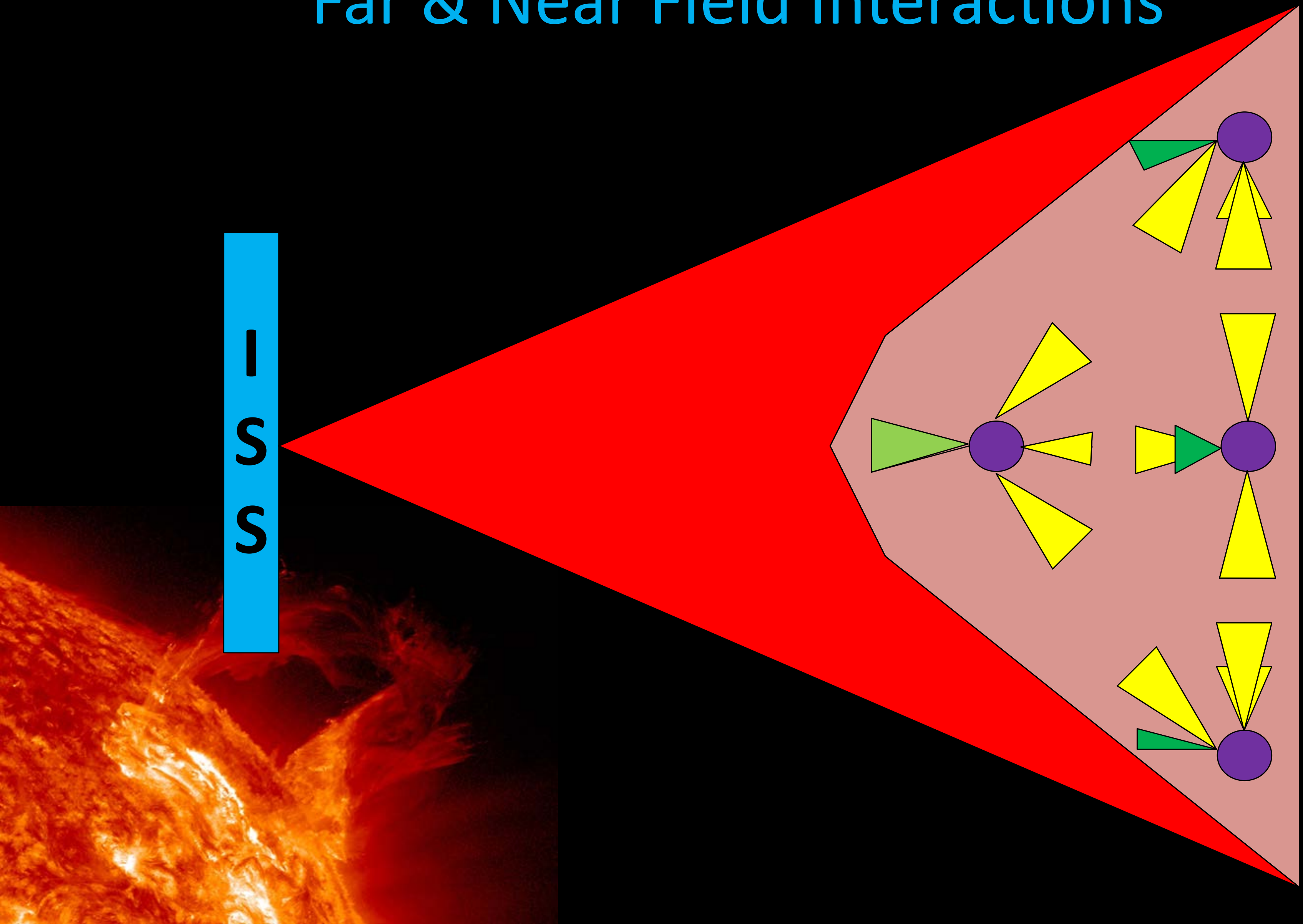
Mathematics of Power Beaming* - Efficiency

DC to Microwave Conversion	Beam Forming Antenna	Free Space Transmission	Reception Conversion to DC
Circa 1992 70 – 90 %	Circa 1992 70 – 97 %	Circa 1992 5 – 95 %	Circa 1992 85 – 92 %

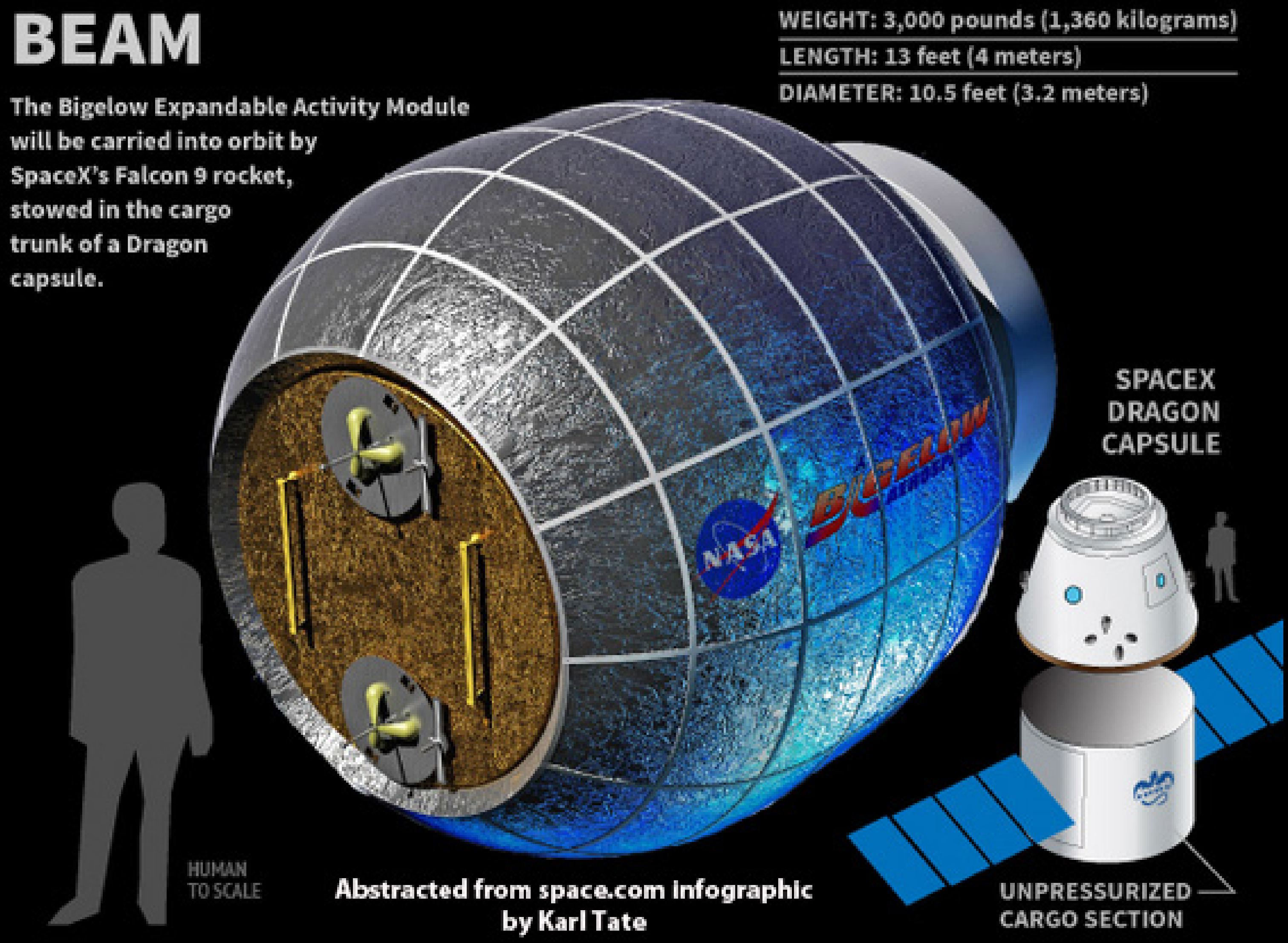
Maximum Possible DC to DC Efficiency --- 76 %
Experimental DC to DC Efficiency --- 54 %
Circa 1992

*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

Beam to Tetrahedral Formation
Far & Near Field Interactions



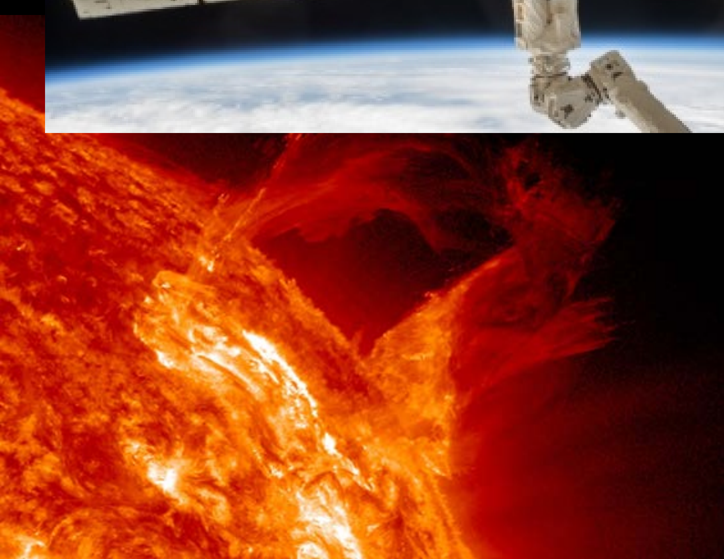
NASA BEAM


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
UNPRESSURIZED CARGO SECTION
HUMAN TO SCALE
NASA
BIGELOW
Abstracted from space.com infographic by Karl Tate

Cygnus & Dragon Freeflyers

Orbital
Innovation You Can Count On®

SPACEX



Technological Challenges

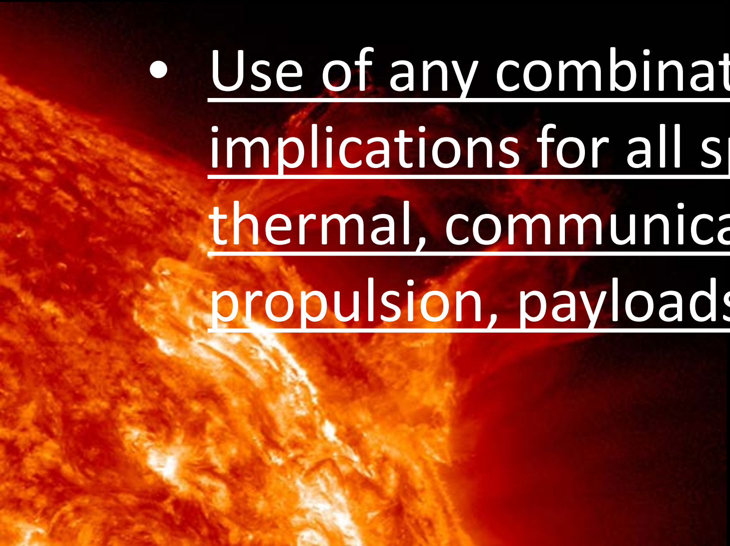
- The first principles physics of both near field and far field energy effects are considered well understood.

- 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.

- <u>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</u>.

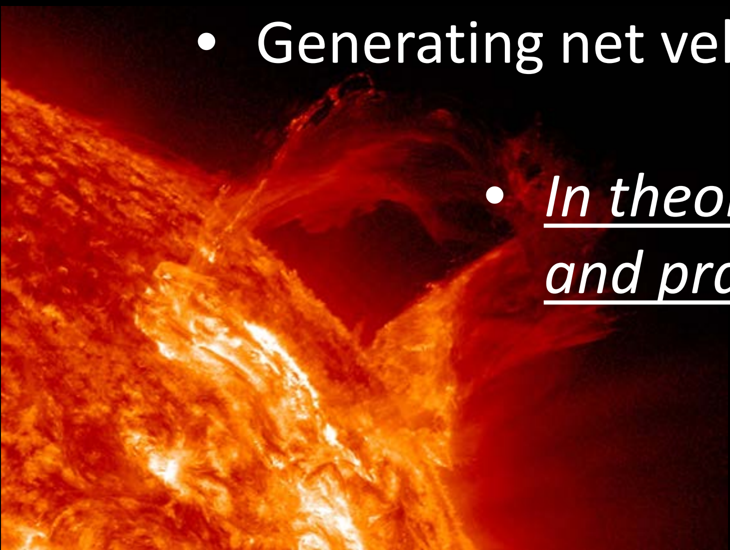
Technological Challenges -2

- Radiant energy components include
  - Electrical
  - Magnetic
  - Linear & Angular Momentum
  - Thermal
  - Data
- There are direct and indirect uses for each component
- <u>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.)</u>



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
  - Generating net outward velocity "push"
  - Generating net inward velocity "pull"
  - Generating net velocity along any specified vector



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

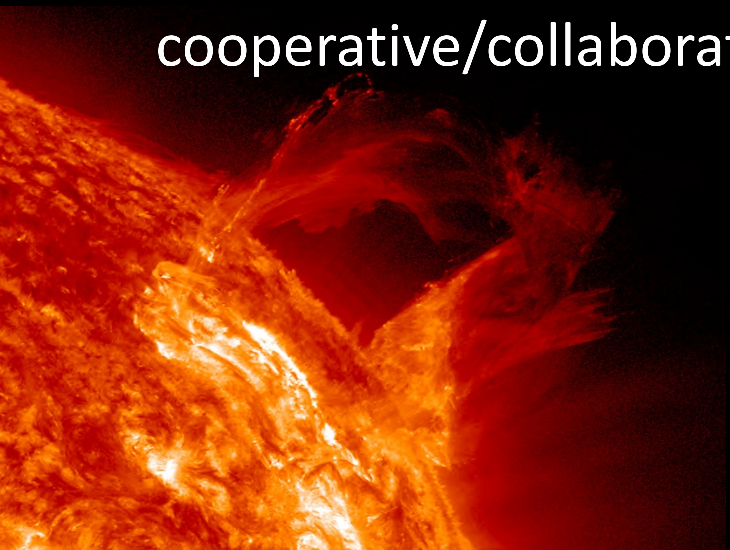
– Jan L.A. van de Snepscheut
computer scientist

The Team Circa Today . . .

- Xtraordinary Innovative Space Partnerships, Inc.
  - Gary Barnhard, et.al.
- Deep Space Industries, Inc
  - Daniel Faber, 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 Research Laboratory – Michael Swartwout, et.al.
- Zero Gravity Solutions - Rich Godwin, et.al.
- Naval Systems Research Lab - Paul Jaffe, et.al
- NASA ARC Mission Control Technologies Lab – Jay Trimble, 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.

Next Steps

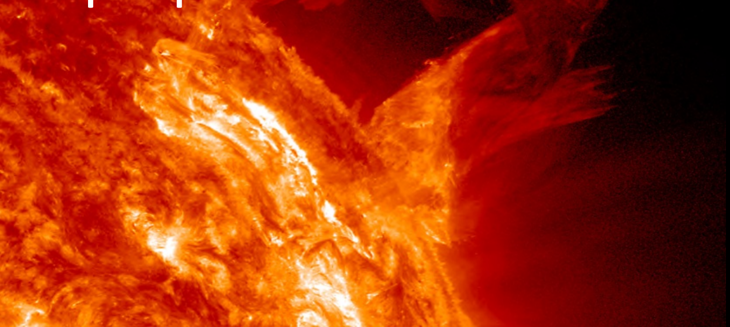
- This is now a commercial mission that will be worked with NASA through some combination of pending and proposed Space Act Agreements.
- Additional partners/participants are being sought in the commercial, academic, non-profit, and government sectors.
- Use of ISS helps ensure that this is an international 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

- Possible Architectures – Exospheres Tool Kit
- Possible Architectures – Spacecraft as Infrastructure
- Reality Check
- Additional Concluding Remarks
- Power System Trade Space Taxonomy Example
- Experiment Phase Definitions
- Optimization Metrics Hypothesizes
- Test Case Definitions for nascent International Space Station Technology Development missions
- Space Communications and Navigation (SCaN) Test Bed (STB) configuration/data

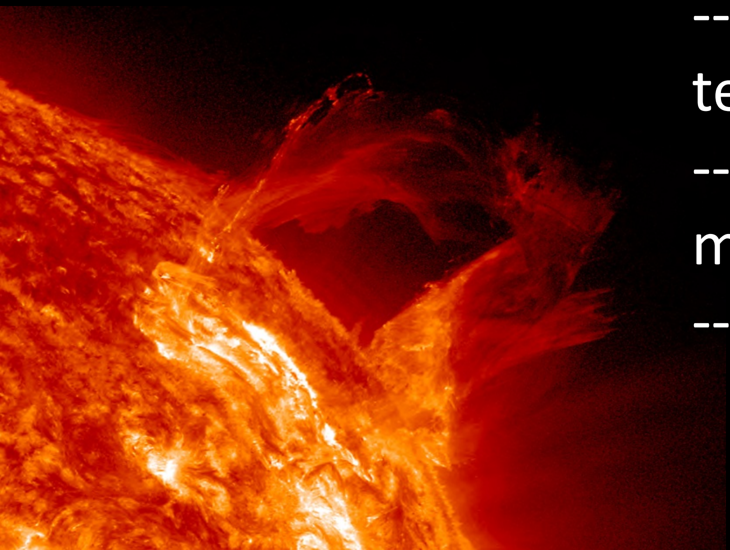
Power System Trade Space - Taxonomy

- 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.

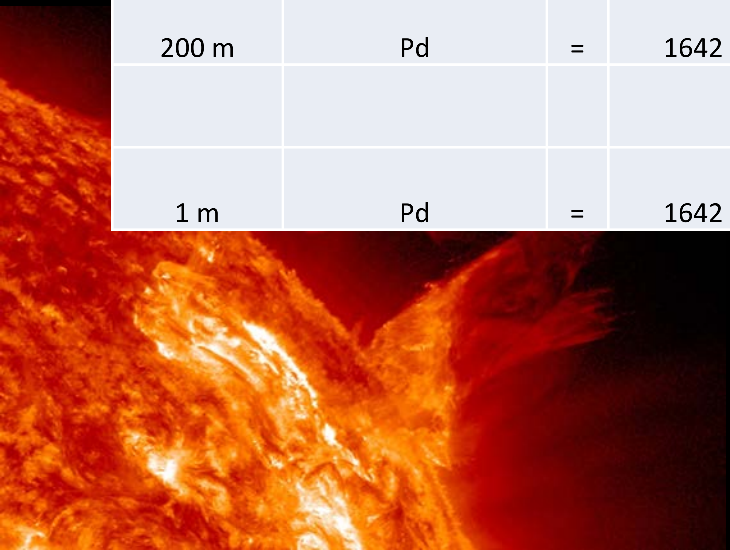
- The innovation must either:

    -- Reduce cost, schedule, and/or technical risk;
    -- Demonstrably enhance the mission; or
    -- Enable the mission



Power Density* - SCaN Test Bed (STB) Solution

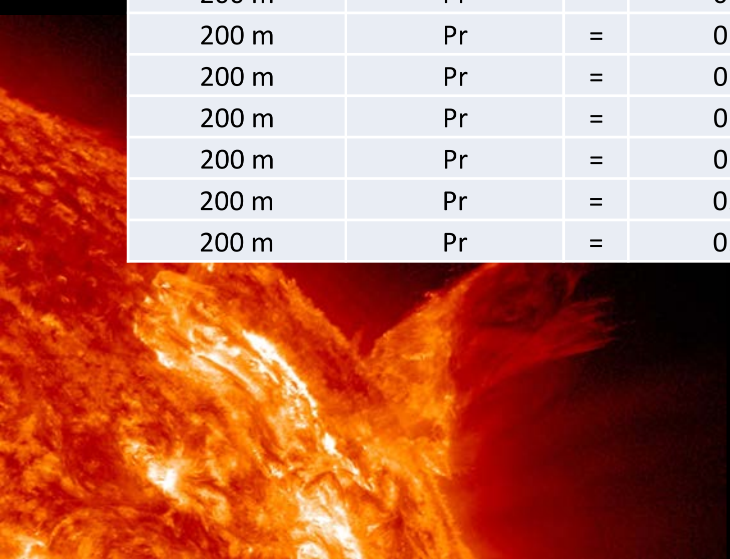
Anticipated Power Density for Several Distances of interest Using SCAN Test Bed (STB) Solution										
	Pd	=	Ai	Pi	/	λ**2	D	D		Pd
	(watts/cm**2)		(cm**2)	(watts)		(cm**2)	(cm)	(cm)		(watts/cm**2)
10 km	Pd	=	1642	40	/	1.2769	1000000	1000000	=	0.00000005
1 km	Pd	=	1642	40	/	1.2769	100000	100000	=	0.00000514
200 m	Pd	=	1642	40	/	1.2769	20000	20000	=	0.00012857
1 m	Pd	=	1642	40	/	1.2769	100	100	=	5.14286861



* On-Orbit SCaN Test Bed (STB) Ka Band Transmitter, 18” Diameter, 40 Watts output power, 26.5 GHz

Power Received* - SCaN Test Bed (STB) Solution

Anticipated Power Received for various rectenna areas								
	Power		Power		Rectenna			
	Received		Density (watts/cm**2)		Area (cm**2)			
	Pr	=	Pd	*	Ar			
200 m	Pr	=	0.000128572	*	100	=	0.01	watts
200 m	Pr	=	0.000128572	*	200	=	0.03	watts
200 m	Pr	=	0.000128572	*	300	=	0.04	watts
200 m	Pr	=	0.000128572	*	400	=	0.05	watts
200 m	Pr	=	0.000128572	*	500	=	0.06	watts
200 m	Pr	=	0.000128572	*	600	=	0.08	watts
200 m	Pr	=	0.000128572	*	1000	=	0.13	watts
200 m	Pr	=	0.000128572	*	4000	=	0.51	watts
200 m	Pr	=	0.000128572	*	5000	=	0.64	watts
200 m	Pr	=	0.000128572	*	6000	=	0.77	watts
200 m	Pr	=	0.000128572	*	6219	=	0.80	watts
200 m	Pr	=	0.000128572	*	7000	=	0.90	watts
200 m	Pr	=	0.000128572	*	7500	=	0.96	watts
200 m	Pr	=	0.000128572	*	8000	=	1.03	watts
200 m	Pr	=	0.000128572	*	9000	=	1.16	watts
200 m	Pr	=	0.000128572	*	10000	=	1.29	watts



* On-Orbit SCaN Test Bed (STB) Ka Band Transmitter, 18” Diameter, 40 Watts output power, 26.5 GHz

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.

Possible Architectures – ExoSpheres Tool Kit

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

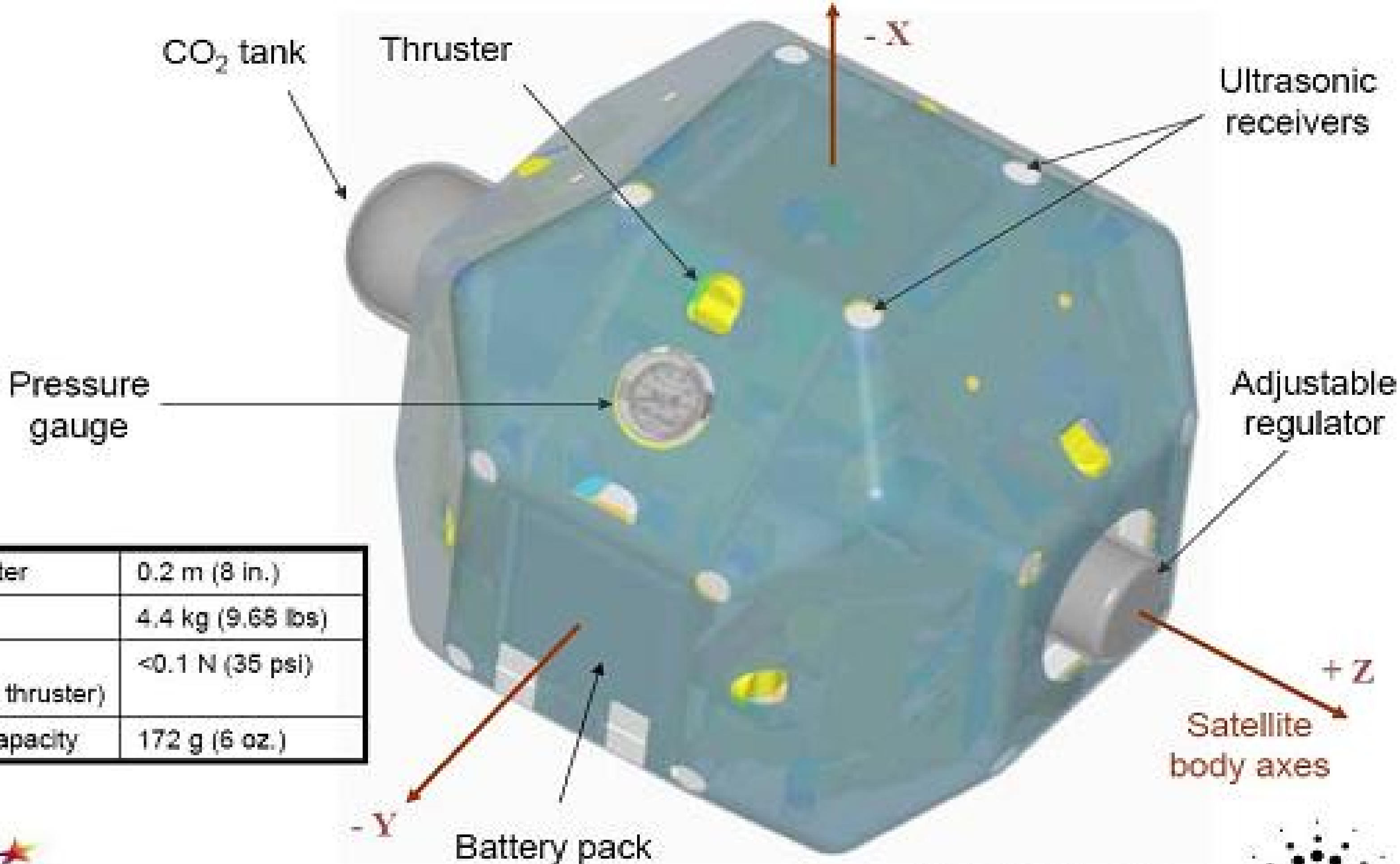
- Multiple unpressurized and pressurized launch opportunities
  - JAXA Kobe Back-Porch launch & retrieve
  - Express Payload Rack launch & retrieve

- 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.)

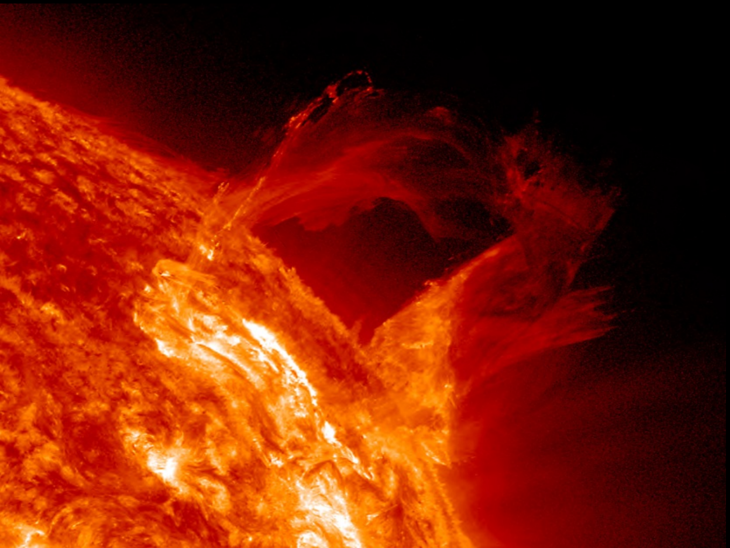
Possible Architectures – Spacecraft as Infrastructure

- 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."

Conclusion - 2

- The successful development of space solar power systems for space-to-space, space-to-lunar/asteroid surface, and/or space-to-Earth use requires the suspension of disbelief across multiple communities of interest.

- There are non-trivial systems engineering challenges that must be must be addressed in any application of space solar power.

- In deference to one of our most spirited colleagues and infamous contrarian on the subject of space solar power . . .

We have some serious “frog kissing” to do to get this right.

Power System Trade Space Taxonomy - 2

1. Energy Sources

1.01 Mechanical

1.02 Chemical

1.03 Nuclear

1.03.01 Radioactive Decay

1.03.02 Fission

1.03.03 Fusion

1.03.03.01 Solar flux

1.03.03.01.01 Direct Solar flux at defined point

1.03.03.01.02 Concentrated Solar Flux at defined point

1.04 Beamed

1.04.01 Microwave

1.04.02 Laser

Power System Trade Space Taxonomy - 3

2. Energy Transducers

2.01 Solar Cells
(Flux ==> electricity)

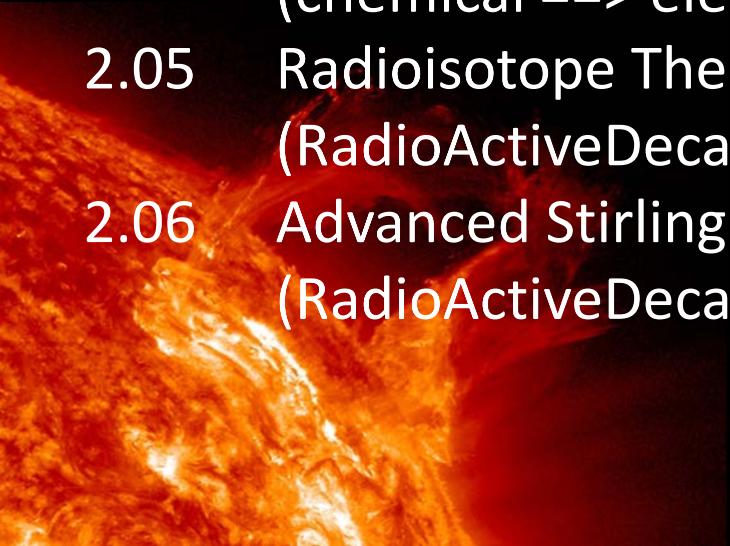
2.02 Solar Dynamic
(Flux ==> heat ==> electricity)

2.03 Flywheel Generator
(kinetic ==> electricity)

2.04 Battery
(chemical ==> electricity)

2.05 Radioisotope Thermal Generator - RTG
(RadioActiveDecay ==> heat ==> electricity)

2.06 Advanced Stirling Radioisotope Generator - ASRG
(RadioActiveDecay ==> heat ==> kinetic ==> electricity)



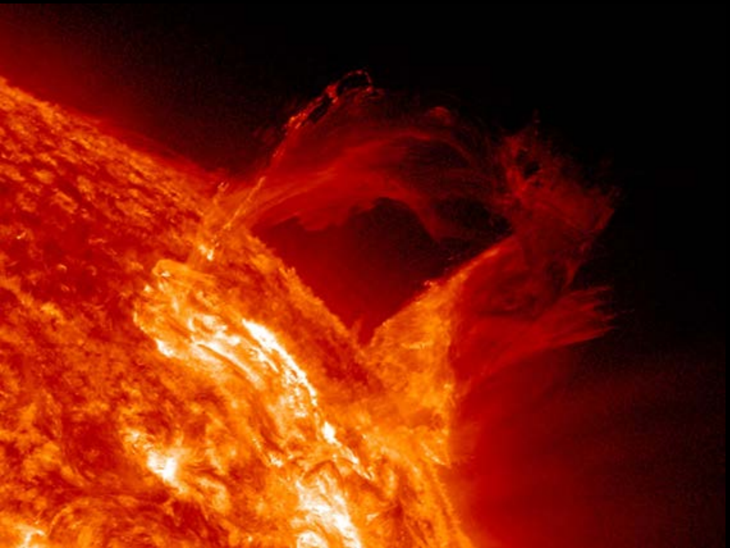
Power System Trade Space Taxonomy - 4

3 Energy Transmission
3.01 Electricity
3.01.01 AC
3.01.02 DC
3.02 Microwave
3.03 Laser
4 Energy Management
4.01 State Monitoring
4.02 System Characterization
4.03 Flow Management
5 Loads
5.01 State Monitoring
5.02 System Characterization
5.03 Flow Management

Optimization Metrics - 1

Test Case One - Reduction in Complexity

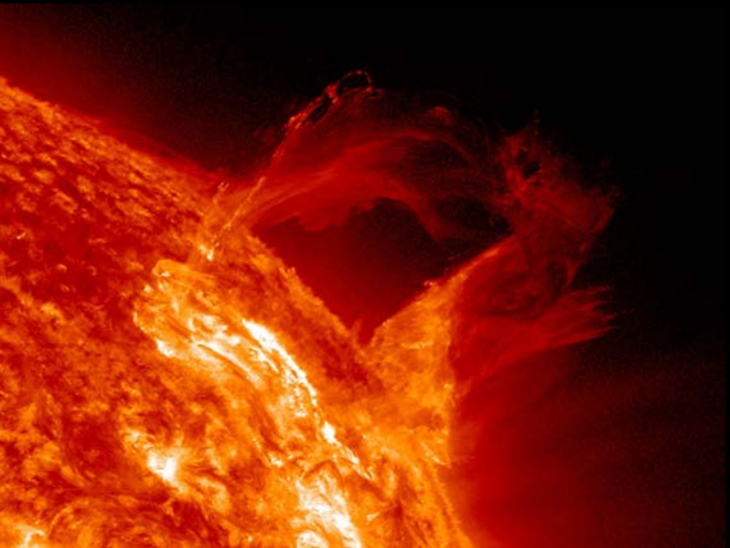
Hypothesis: *if the design of a power system for a spacecraft emerges as a driving factor in increasing the complexity of the overall flight system to be supported, the decoupling / unbundling / reapportionment of the power system could significantly impact cost, schedule, and technical risk.*



Optimization Metrics - 2

Test Case Two - Reduction in Mass and/or Volume

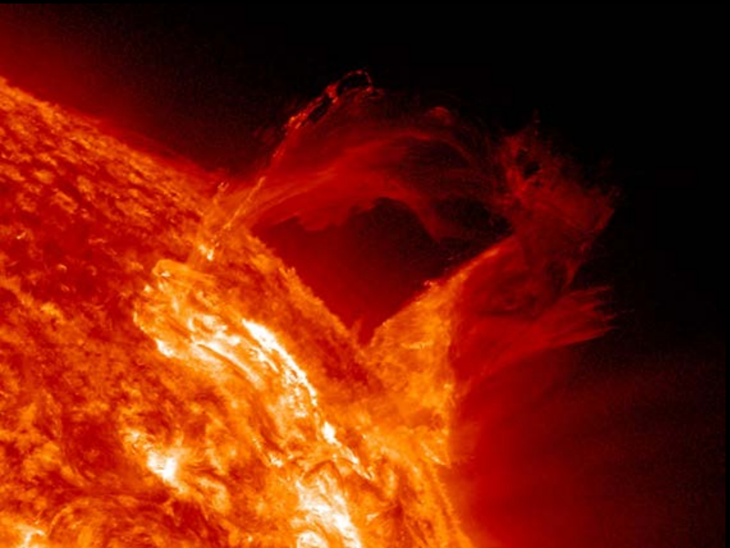
Hypothesis*: if the available mass and volume budgets assigned to a power system and their apportionment to the subsystems that make up that system, materially impact the design of the overall flight system to be supported, their reapportionment could significantly impact cost, schedule, and technical risk.*



Optimization Metrics - 3

Test Case Three - Additional delta-V

Hypothesis: *if the beaming of energy to a spacecraft can be translated into additional delta-V through increasing the available electrical power and/or providing an auxilary source of heat, the design of the overall flight system to be supported could be impacted in a manner that is mission enhancing if not mission enabling.*



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

Test Case 1 - Complexity

Source: Fusion, Solar Flux, LEO

Transducer: Solar Cells (ISS Power System)

Storage: Batteries (ISS),
Keep-Alive (Co-Orbiting Free Flyer)

Transmission: express payload pallet mounted variable frequency microwave transmitter with collimation

Loads: passive/active alignment target/ signal, rectenna

System Mgmt: apportioned as needed, bi-directional command, control, and telemetry

Test Case 1 – Complexity (Cont'd)

Flight System: Deployable, crew tended free-flyer with docking port and accommodations for micro-gravity test and manufacturing cells as well as other highly disturbance sensitive experiments. Supports power data grapple fixture interface for berthing. Supports Modular, Adaptive, Reconfigurable System (MARS) implementation for backup stabilization and attitude control.

Optimization Objective: Reduce the complexity of the overall free-flyer system while meeting or exceeding the requirements for the classes of payloads intended to be served.

Test Case 2 – Mass/Volume

Source: Fusion, Solar Flux, LEO

Transducer: Solar Cells (ISS Power System)

Storage: Batteries (ISS),
Keep-Alive (Co-Orbiting Free Flyer)

Transmission: express payload pallet mounted variable frequency microwave transmitter with collimation

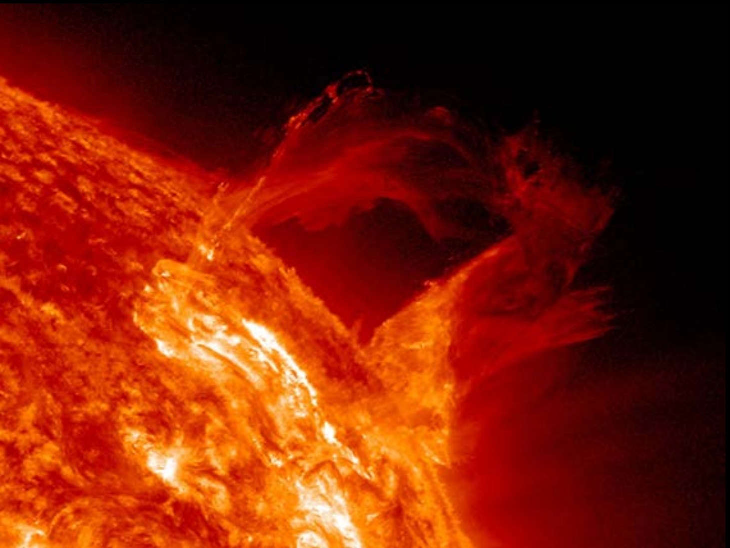
Loads: passive/active alignment target/ signal, rectenna

System Mgmt: apportioned as needed, bi-directional command, control, and telemetry

Test Case 2 – Mass/Volume (Cont’d)

Flight System: Deployable, cubesat / exosphere like system incorporating multiple solutions for energy reception and near-network relationship management

Optimization Objective: Reduce the mass and/or volume of the overall free-flyer system while meeting or exceeding the requirements for the classes of payloads intended to be served.



Test Case 3 – delta V

Source: Fusion, Solar Flux, LEO

Transducer: Solar Cells (ISS Power System)

Storage: Batteries (ISS),
Keep-Alive (Co-Orbiting Free Flyer)

Transmission: express payload pallet mounted variable frequency microwave transmitter with collimation

Loads: passive/active alignment target/ signal, rectenna

System Mgmt: apportioned as needed, bi-directional command, control, and telemetry

Test Case 3 – delta V (Cont'd)

Flight System: Deployable, cubesat/exosphere like system incorporating multiple solutions for energy reception, electric propulsion/attraction, and near-network relationship management.

Optimization Objective: Demonstrate that beamed energy can provide a material increase in outbound delta V and in some cases an attractive force, thereby augmenting the resources available for propulsion on an appropriately provisioned spacecraft.

SCaN Testbed on ISS

- The Radio Frequency (RF) Subsystem is comprised of a Traveling Wave Tube Amplifier (TWTA), Coaxial Transfer Switches, Antennas, Diplexers, an RF Isolator, an RF Attenuator, and transmission lines to interconnect the RF Subsystem components with the radios.

- The RF Subsystem radiates RF signals intended for TDRS and the ground; and receives RF signals from TDRS, the ground, and the GPS system.

- The architecture of the SCaN Testbed has the ability to send RF signals from two separate SDRs to two antennas simultaneously.

SCaN Testbed on ISS

- The ability to send RF signals from two separate SDRs to the same antenna or from a single radio to two different antennas is not supported by the architecture and cannot happen due to switch positions required.

- The RF Subsystem contains four active devices: the TWTA and three switches.

- All components that comprise each of the three RF paths; Ka-band, S-band, and L-band are shown in Figure 3-5.

- The RF Subsystem interfaces with the Avionic Subsystem, the Flight Enclosure, the Antenna Pointing Subsystem, and the three Radios.

SCaN Testbed on ISS

- The TWTA is a Ka-band high power amplifier that can generate up to 40 watts of microwave RF power.

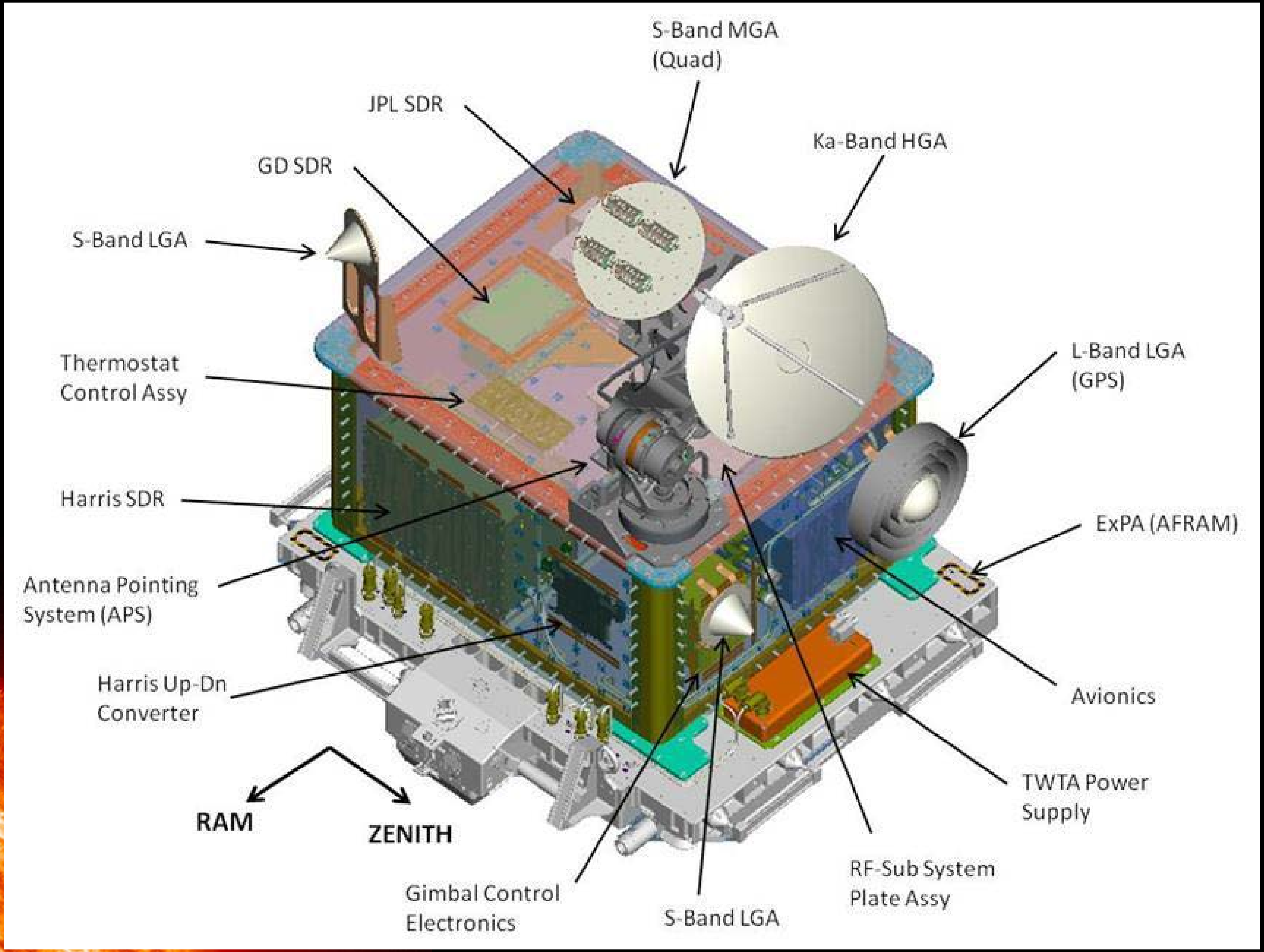
- The Avionics Subsystem controls the TWTA through both a discrete logic command interface and the 28 Vdc power supplied from the TWTA Power Supply Unit (PSU).

- The TWTA was developed and provided by L-3 Communications.

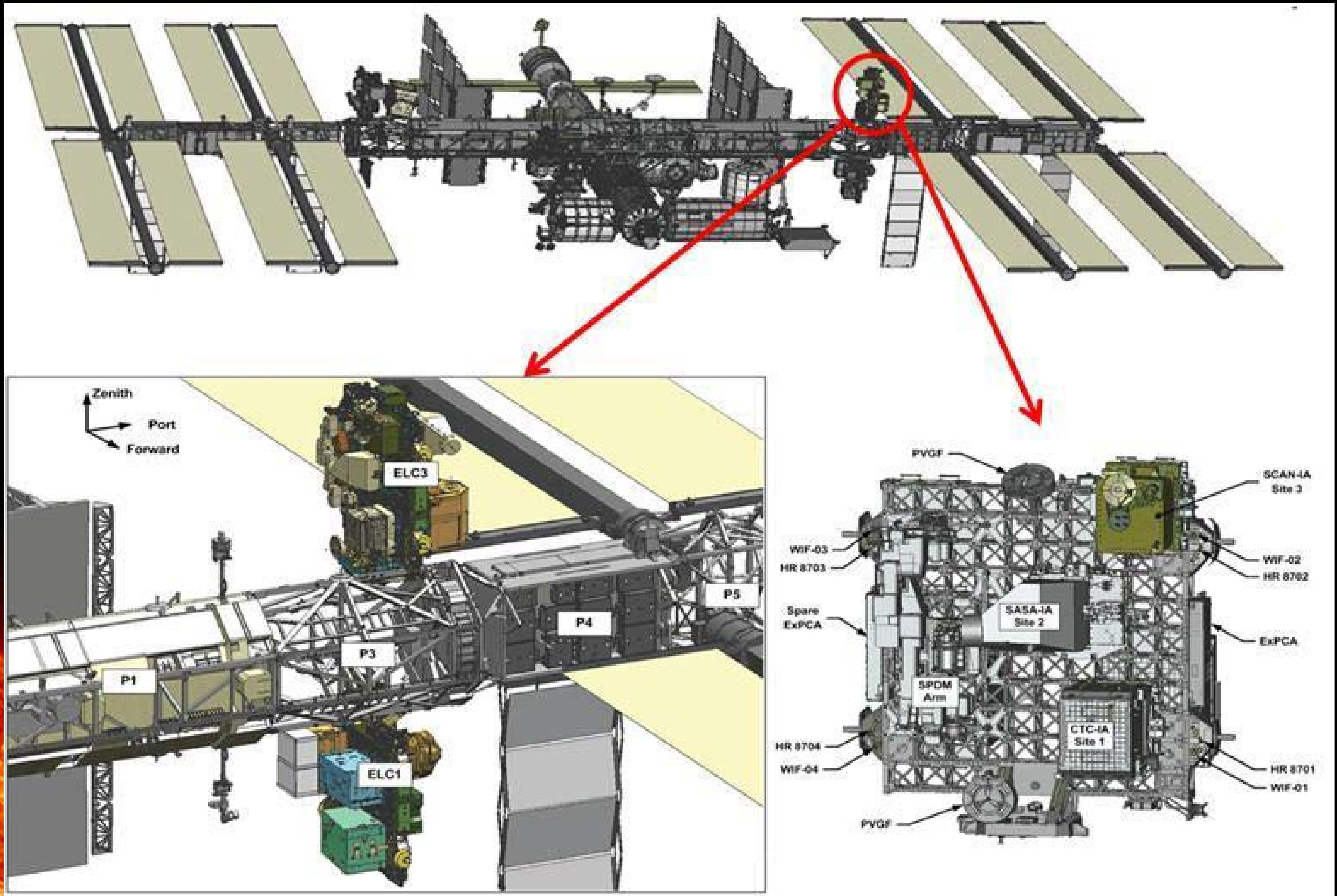
- The TWTA PSU converts 120Vdc from ISS to 28Vdc for use by the TWTA.

- The TWTA must be actively commanded by the Avionics Subsystem to operate.

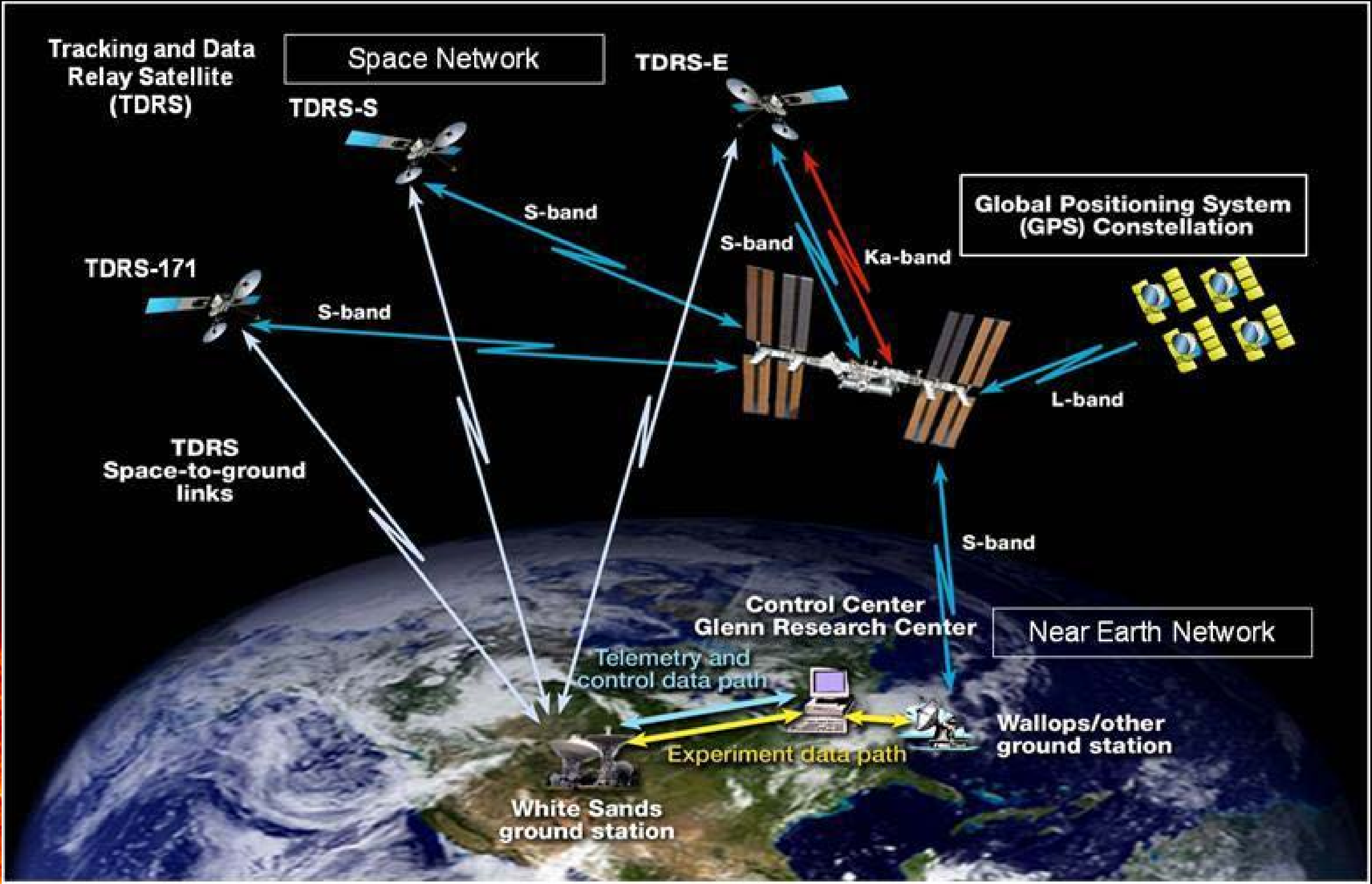
ISS SCaN Testbed Components



ISS SCaN Testbed Location



SCaN Testbed System Overview



Possible Architectures – Cubesat Swarm

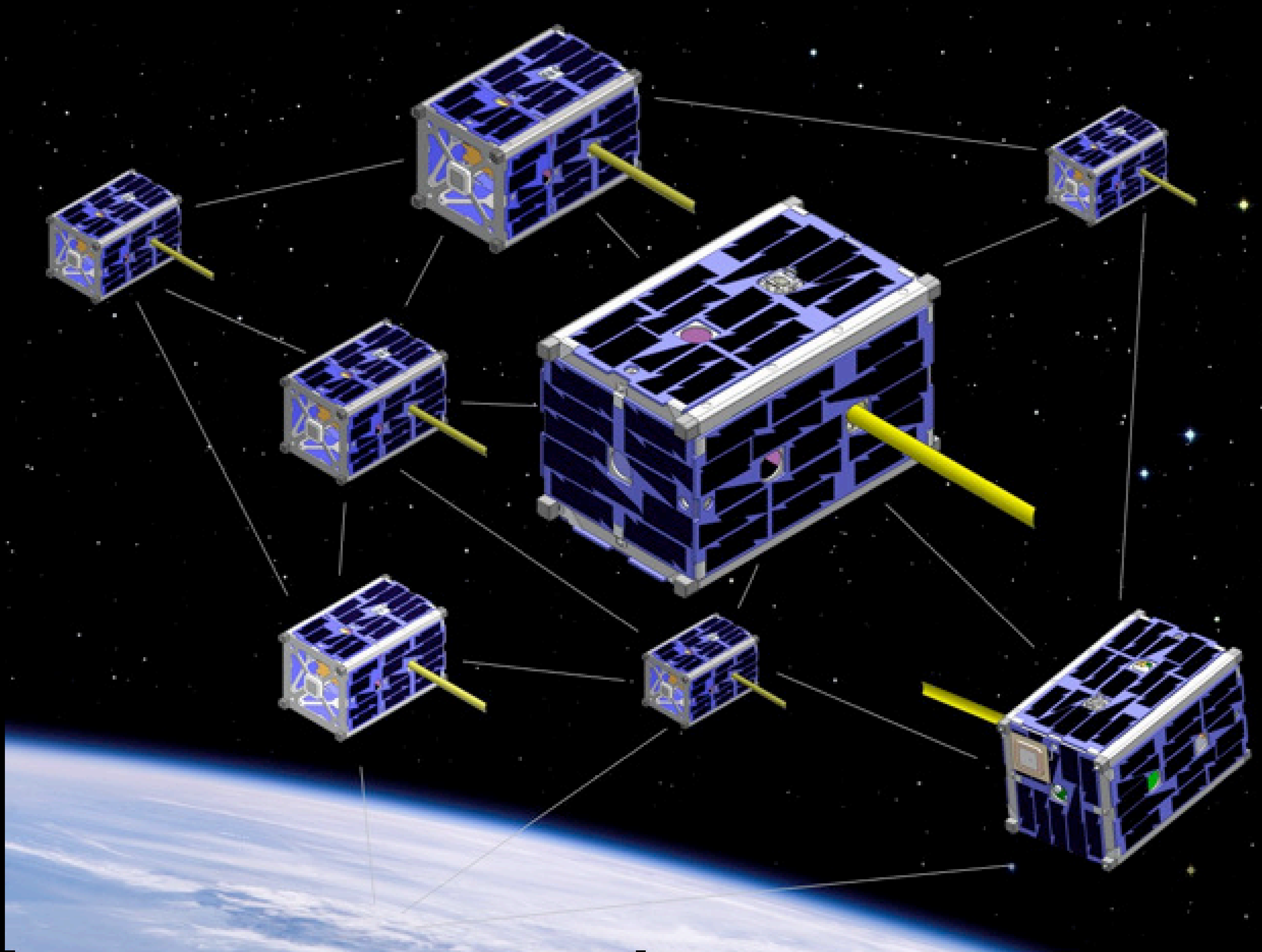
- All three test cases applicable
  - Reduction in complexity
  - Reduction in mass and/or volume
  - Provide delta V
- Multiple unpressurized and pressurized launch opportunities
  - Logistics Carrier Deployment
  - JAXA JEM Kibo Back-Porch launch & retrieve
  - Express Payload Rack launch & retrieve
- 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

JAXA Kibo robotic arm deploying cubesats

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.

Notional Cubesat Swarm



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 six 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 0 Mission Definition, Planning & Management
- Task 1 Requirements Definition
- Task 2 Interface Definition/Characterization
- Task 3 Testbed Implementation
- Task 4 Application Coding & Hardware Definition
- Task 5 Verification & Validation
- Task 6 Technology Demonstration
- Task 7 Reporting, Presentations, and Identification of Follow-on Work

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

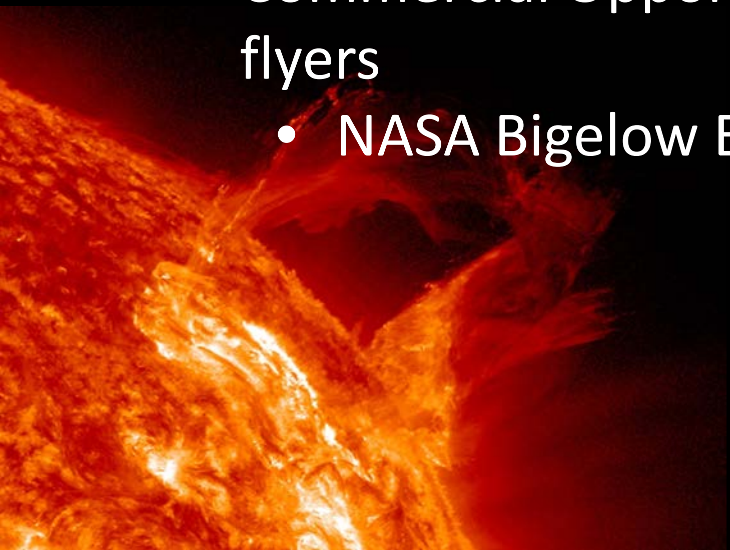
- Several potential research opportunities have emerged that could make use of a combination of resources currently available or that can be readily added to ISS:
- Of particular interest is the use of one or more of the available Ka band (27 to 40 Ghz) communications transmitters on ISS as well as the 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.

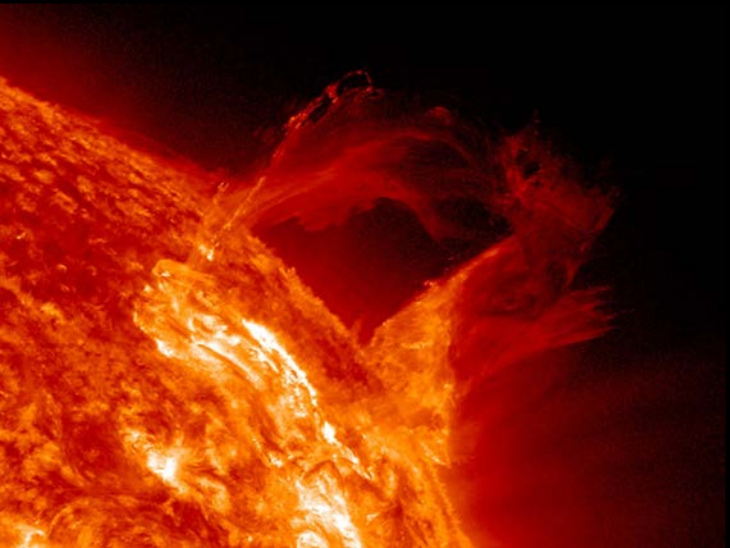
Possible Architectures – Co-orbiting Free-Flyers

- 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)



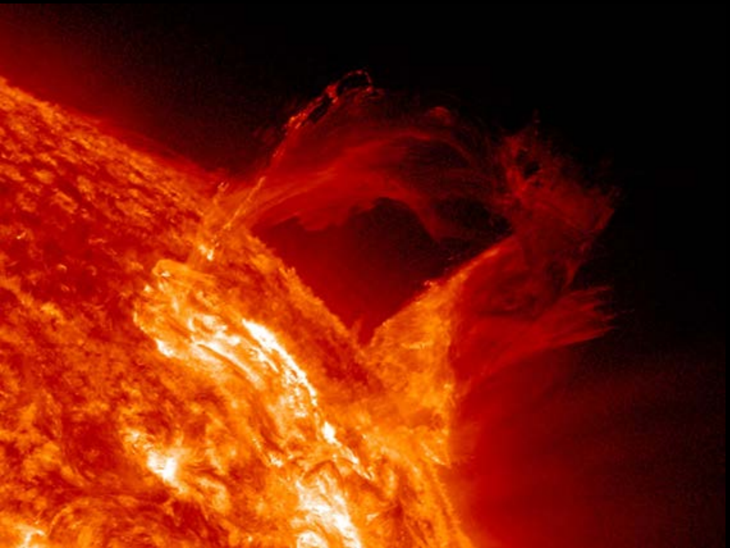
Crew Tended Freeflyer Considerations

- 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.



MCT Experiment Vector Objectives

1. Defining and implementing/prototyping a parametric state model for integrated end-to-end mission operations control applications of technology development and demonstration mission prototype, test and flight articles.
2. This includes development of near real-time state models of the transmitter, the radiant energy beam, and the flight test article(s) operating within the MCT framework/environment at four levels:



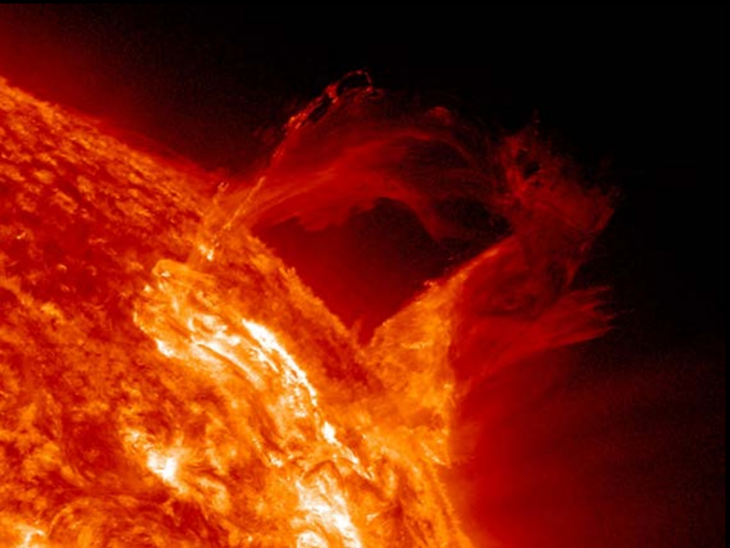
MCT Experiment Products Year 1

1. development of a paper model and individual element protocode;
2. development of functioning individual element models and an end-to-end model protocode;
3. optimization of individual element models and a functioning end-to-end model;
4. testing of the optimized end-to-end model and individual element models in mixed modes (protoflight hardware and software with simulation as needed).

MCT Experiment Vector Products Years 2 & 3

Year 2 activities will focus on actual on-orbit demonstrations and testing the efficacy of the near realtime parametric state model developed in year 1.

Year 3 activities will focus on assessing, reviewing, and establishing the efficacy of applying the near real-time parametric state models to current and future technology development missions beyond power beaming.



ESA ATV & JAXA HTV Freeflyers