Technology Development, Demonstration, and Deployment (TD^3) Missions: Biasing opportunities towards better outcomes for Cislunar and beyond

AIAA Space Automation and Robotics Technical Committee (SARTC)
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Outline

(1) What is XISP-Inc!?
(2) The Problem Space . . .
(3) Finding Nexus . . .
(4) Traversing the “Valley of Death”
(5) XISP-Inc evolving TD^3 mission set
(6) XISP-Inc mission potential outcomes
(7) Leverageable opportunities discussion

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(8) Backup Charts -- XISP-Inc TD^3 mission set in more detail
- Space Solar Power and ancillary services Beaming (SSPB)
- Management Operations Control Applications (MOCA)
- Interoperable Network Communication Architectures (INCA)
- Alpha Cube Sat (ACS)
- Halfway To Anywhere (HTA)

What is XISP-Inc!?

- Xtraordinary Innovative Space Partnerships, Inc (XISP-Inc) is a virtual enterprise headquartered in Cabin John, Maryland.
- XISP-Inc is a U.S. for-profit entity focused on the creation of Cislunar Technology Development, Demonstration, and Deployment (TD^3) missions and the Public Private Partnerships to execute them.
- XISP-Inc includes over 25 staff/consultants, as well as a consortium of companies, universities, non-profit entities, and cooperating agencies associated with the mission development work in various capacities.
- XISP-Inc staff/consultants have a wide range of experience spanning every phase of space mission development and execution, and scale from cubesats to the ISS.
- XISP-Inc staff/consultants have extensive specialized experience in computer, robotics, power, and space systems engineering supporting NASA and a wide range of other entities.

The Problem Space . . .

- N-Dimensional interaction problems (i.e., an arbitrary number of objects interacting in an arbitrary number of ways) are a class of problems for which the generalized solution space is typically computationally intractable in any time frame.
- Space automation and robotics present a subset of these problems that exacerbates the situation by requiring near real-time solutions in many instances.

Reality is not a convenient problem or solution space . . .

Finding Nexus . . .

- Nexus in this case is the intersection between *theoretical constructs* of knowledge-based-systems and space systems engineering reduced to *practice*.
- XISP-Inc mission development efforts can be viewed as a set of *conceptual threads* intended to draw out the confluence of interests *needed to bias work towards better outcomes* for Cislunar and beyond space missions.
- The process goal is to *reverse engineer the desired outcomes* by orchestrating a combination of technology development “push” and mission requirements “pull”

Traversing the Valley of Death . . .

- There is a virtual cornucopia of Intellectual Property stranded on the wrong side of the Technology Development **"Valley of Death"** for a myriad of reasons which XISP-Inc seeks to leverage.
- XISP-Inc mission development efforts focus on Technology Development, Demonstration, and Deployment TD^3 missions.
- This approach supports the aggregation of IP, identification of the stakeholders, codification of the IP commons and claims, and drawing out the confluence of interests for various applications.
- This approach can effectively *bridge the "valley of death"* for technologies that otherwise might never be brought to fruition.

XISP-Inc Evolving TD^3 Mission Set

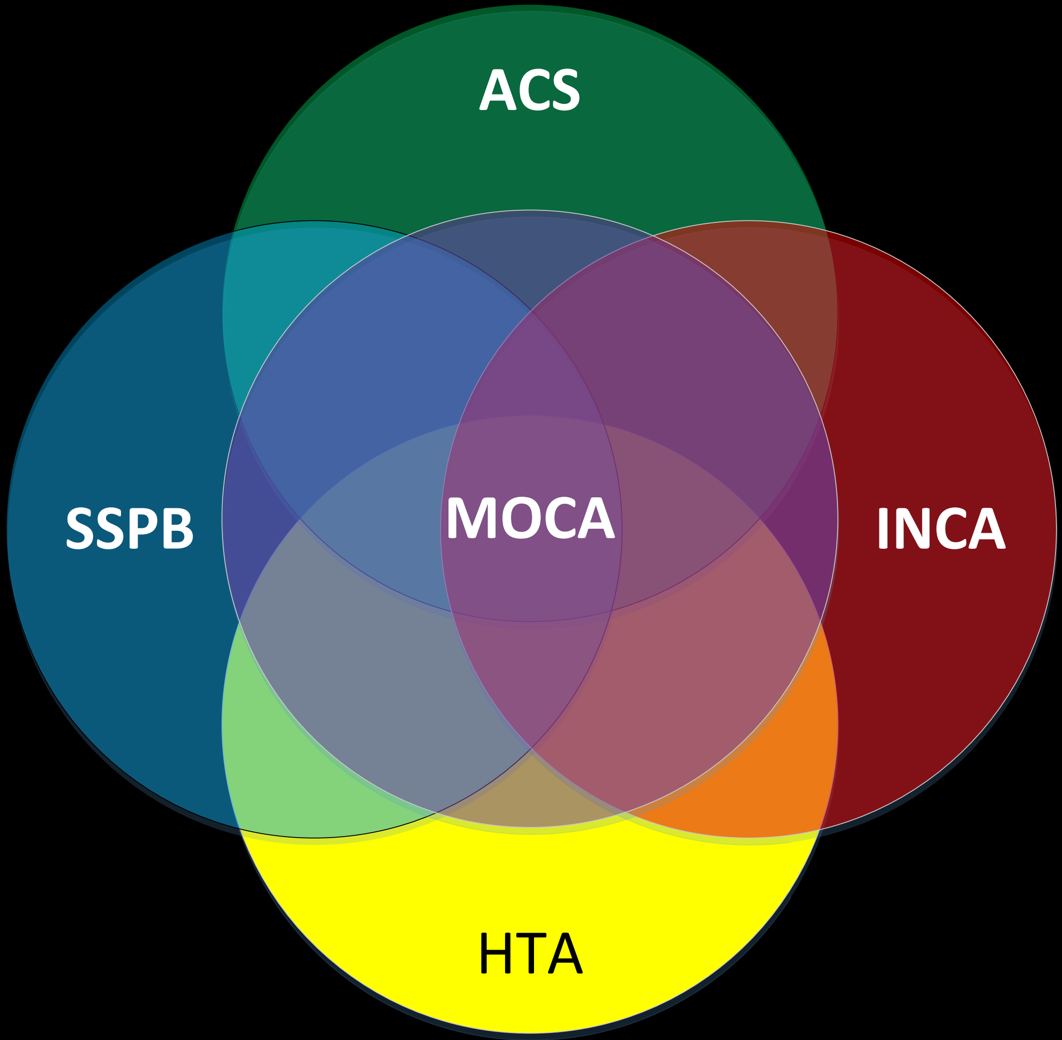
Alpha Cube Sat (ACS)

Space-to-Space Power Beaming (SSPB) & Ancillary Services

Mission Operations Control Applications (MOCA)

Interoperable Network Communication Architecture (INCA)

Halfway To Anywhere (HTA)



XISP-Inc Mission Potential Outcomes

- Space Solar Power and ancillary services Beaming (SSPB)
  - Effective use of radiant energy beam components

  → Cislunar Electrical Utility - Lunar Power & Light Company
- Interoperable Network Communications Architecture (INCA)
  - Near real-time link characterization, pervasively networked DTN gateway/QoS Routing, virtualization of functions

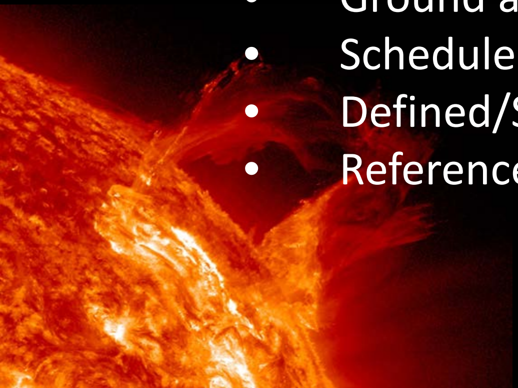
  → Automated Telco Central Office Functionality (cognitive software defined transceivers, gateways, and hardware/software resources allowing dynamically allocated QoS communications services)
- Management Operations Control Applications (MOCA)
  - Framework for supporting a mutable locus of control between teleoperation and autonomy on a shared control basis, advanced vision and task area recognition (AVaTAR)

  → Dramatic improvements in speed, efficiency, and safety for EVR and combined EVA/EVR tasks
- Team Alpha CubeSat (ACS) Technology Demonstration System
  - NASA Cube Quest Challenge Entry Deep Space & Lunar Derbies

  → Virtual Operations Center, Advanced Technology CubeSats, Autonomous Navigation, Electro-optical Interferometry

Leverageable Opportunities Discussion (1 of 2)

- **Space Solar Power and ancillary services Beaming (SSPB)**
  - ISS Power and ancillary services beaming testbed
  - MOCA overlay of INCA-A guest experiment on LCRD
  - CLPS & HLS payloads in coordination with the Lunar Surface Innovation Consortium
- **Interoperable Network Communications Architecture (INCA)**
  - INCA-A guest experiment on LCRD, near real time link characterization
  - Support of multiple Management Operations Control Applications (MOCA) overlays
  - Extend INCA-A to ISS & Illuma-T
  - Extend INCA-A to other cooperative targets
  - Extend INCA-A to Visible and Active Space Tracking (VAST) autonomous navigation
  - Extend INCA-A to Cislunar Wide Area Network
- **Management Operations Control Applications (MOCA)**
  - Establish a framework for a mutable locus of shared control between:
    - Remotely Supervised, Teleoperated, Physically Present, and Autonomous Operations
    - Ground and Inflight Operations,
    - Scheduled/Dynamic Operations
    - Defined/Sensed Environments
    - Referenced, Predicted, and Sensed Geometry



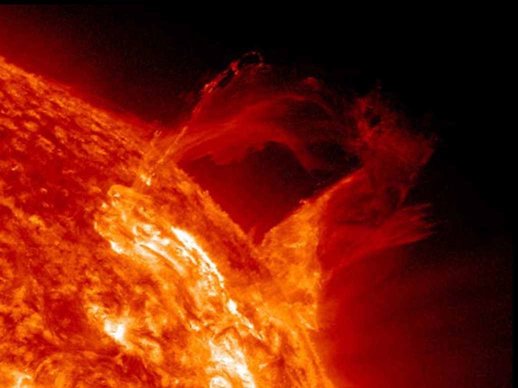
Leverageable Opportunities Discussion (2 of 2)

- **Team Alpha CubeSat (ACS) Technology Demonstration Systems**
  - NASA Cube Quest Challenge Entry Deep Space Derby (Primary) & Lunar Derby (Secondary)
  - Geometric Rideshare Opportunities
  - Virtual Operations Center
  - Advanced Technology CubeSats
  - Autonomous Navigation
  - Electro-optical Interferometry
- **Halfway To Anywhere**
  - Advanced cube sat propulsion system early flight opportunities
  - Alternate minimum energy trajectory manifold solutions
- Geometric Space Mars Missions of Opportunity Challenge Matrix
  - Cooperate/Collaborate in filling in the advantageous payload details
- MIT Haystack Observatory
  - Join the XISP-Inc Mission Development Consortium

Backup Slides

XISP-Inc TD^3 mission set in more detail

- **Space Solar Power and ancillary services Beaming (SSPB)**
- **Management Operations Control Applications (MOCA)**
- **Interoperable Network Communication Architectures (INCA)**
- **Alpha Cube Sat (ACS)**
- **Halfway To Anywhere (HTA)**



Example 1: Power & Ancillary Services

PROBLEM: The availability of power and ancillary services (e.g., communications, data, navigation, time, etc.) is essential to most if not all aspects of Cislunar operations.

HYPOTHESIS: Unbundling/disaggregating power systems (i.e. the separation of power generation, transmission, control, storage, and loads) can:

- allow the reduction and/or reallocation of complexity, mass and/or volume
- alter the cadence of mission operations
- reduce, eliminate, or deconflict solar pointing and other technology specific requirements and constraints
- impart additional delta-V to spacecraft/debris
  - indirectly (power augmentation)   - directly (momentum transfer)
- Foster the identification and effective use of synergies between technologies venues, and applications.

OUTCOME: Increasing the availability of power and data transfer performance while simultaneously reducing the resource burden (mass, power, volume) to achieve the same that must be borne by the Clients/Customers will be mission enhancing if not mission enabling.

Critical Considerations (1)

- Space Power and Ancillary Services infrastructure is an applied engineering problem and an economics problem.
  - Applied Engineering because the solutions are valued in terms of availability, durability, resilience, and maintainability not as new science and/or engineering
  - Economics because the solutions are necessarily sustainable utilities that will circumscribe what is possible
- Each application and venue has:
  - significant systems engineering and economic challenges
  - different fundamental figures of merit / value proposition.
- Operational capabilities are best realized by leveraging a combination of technology development “Push” and mission requirements “Pull”.

Critical Considerations (2)

- Work Vectors:

Technology: Development ➔ Demonstration ➔ Deployment
Venues: Space-to-Space ➔ Surface-to-Surface
➔ Space-to-Alternate Surface ➔ Space-to-Earth

- *Each increment of public and/or private investment* should lead to an *operational capability* useful and used by one more other missions.
- The *efficacy* of any systems architecture *must consider the entire lifecycle of fielded equipment* with respect to cost analysis, functionality, scalability, durability, and maintainability.
- *Engineering solutions which leverage other mission investments should be given priority, but not exclusivity*.
- Furthermore, approaches should be biased to organically grow the community of interest so they become increasingly invested in the success of the endeavors.

Key Variables

- **Cost/Economics** (initial cost to first power, Levelized Cost of Electricity, market viability, anchor customers),
- **Magnitude** (power level supporting applications, scalability)
- **Distance** (near field, boundary regions, far field),
- **Frequency/Wavelength** (microwave to eye-safe optical),
- **Voltage/Amperage** (input, output, transforms)
- **Duration** (pulsed, scheduled, continuous),
- **Availability** (dispatchable, on demand, scheduled, prioritized, by exception, resilience, interoperability),
- **Security** (misuse, interruption, destruction, safety),
- **Performance** (net transfer, end-to-end efficiency, piecewise efficiency, steering precision and accuracy, beam shaping, effective operational difference),
- **Logistics** (mass, volume, modularity, durability, maintainability),
- **Environmental** (temperature, radiation, degradation), and
- **Technology Readiness Level** [TRL] (cost, schedule, and technical risk)

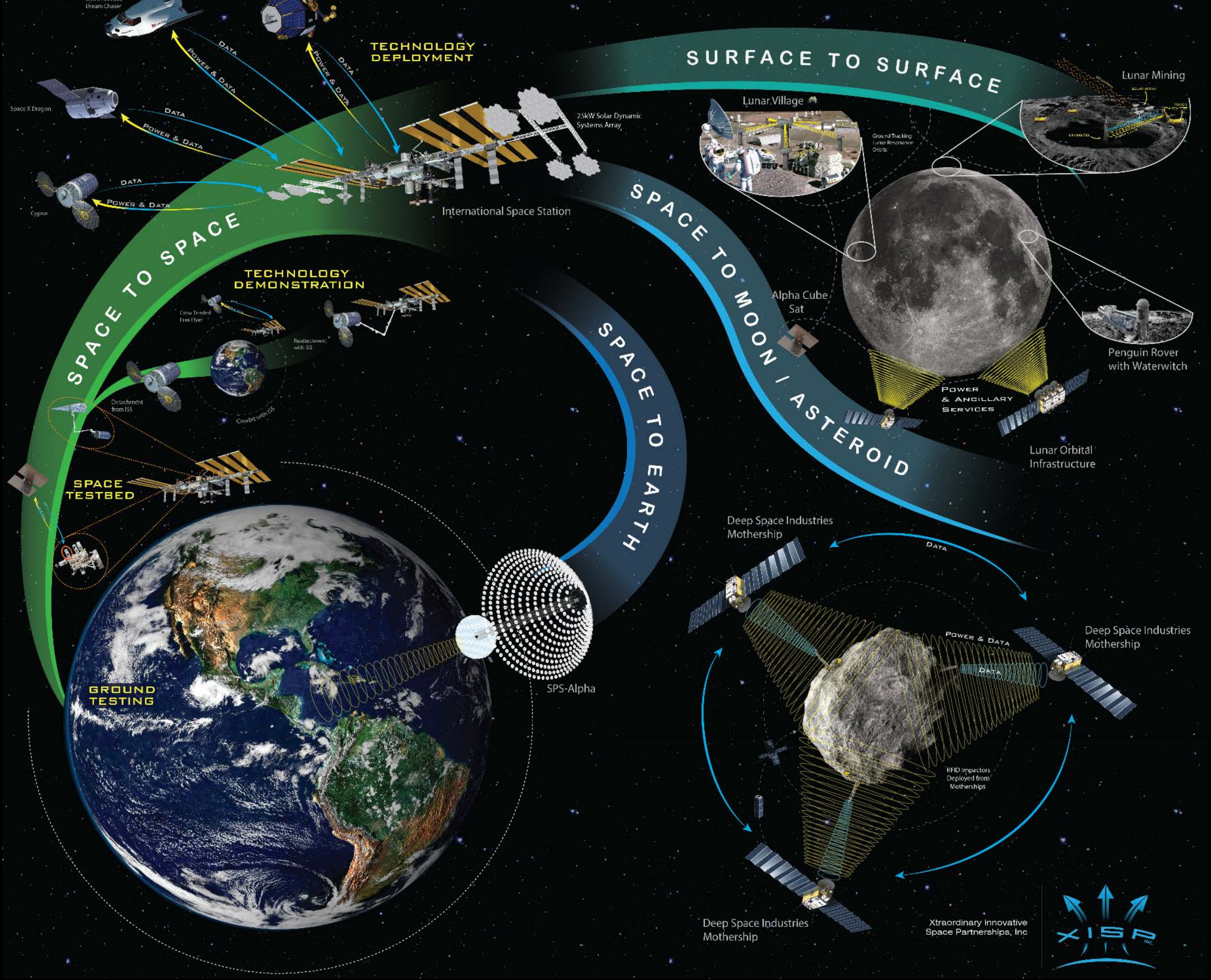
Space Solar Power Challenge Matrix

TRL Advancement

Relative Value of Delivered Power

Venues	Space Solar Power Problem Space		Space Solar Power Solution Space	
	Technology Development		Operational Capability/Applications	
	Ground	Space	Technology Demonstration	Technology Deployment
Space - to - Space	• Cognitive SDR Transceiver • Converged Electro/Optics • W Band & Optical Apertures • Piecewise Efficiency • Reflectarray Rectenna • Beam Forming • Transducers (heat engines, CPV, TPV, fuel cells) • Mgmt Ops Cont.App (MOCA)	• ISS Mounted Transceiver • Deployable Rectenna • 6U Flight Test Article • Optimized Frequencies • End-to-End Efficiency • Scaling/Modularity (Gen, Trans, Stor, Dist, and Cont) • Multiplexing Services • MOCA S/W & Data System	• ISS Co-orbiting Crew Tended Free Flyer Demo • Propulsion Augment Demo • Space Based Propellant Depot Operations Demo • Disaggregated Formation Flying Spacecraft Demo • Plug in/Plug Out Tech Demo • Solar Dynamic Demo	• Power & Ancillary Services Beaming Interface Kit(s) • Dispatchable Power & Ancillary Services • Cislunar Propulsion Services • Kilowatt scale services
Surface - to - Surface	• Deployable Power Generation & Relay Towers • Conformal Rectenna • Deployable Rectenna • Solar Concentrator/Reflector • Interoperable Heat Engines	• Powered Rover • Powered Prospector • Powered Miner • Volatile/Metal Separation • Interoperable Heat Engines	• Power & Ancillary Services Beaming - Survive the Night • Volatiles Mining Demo • Propellant Depot Demo • Metals Mining Demo • Interoperable Heat Engines	• Dispatchable Power & Ancillary Services • 24x7 Operations Support • Kilowatt to Megawatt Scale Services • Interoperable Power Service
Space - to - Moon / Asteroid	• Disaggregatable Flight Systems Technology • Scalable Transceiver • Scalable/Printable Rectenna • Management Operations Control Applications (MOCA)	• Mothership with deployable sensors/rovers • Distributable Rectenna • Lunar Resonant Orbits • Beam Steering (Phased Array & Gimbals) • Scalable, Modular, Maintainable Heat Engines	• Power & Ancillary Services Beaming Demo • Lunar Assay & Mining Demo • Asteroidal Assay & Water/ Volatiles Mining Demo • Asteroidal Optical Drilling, Volatiles Mining & Demo • Metal Refining Demo • Planetary Defense	• Synergistic impact of Cislunar Development • Dispatchable Power & Ancillary Services • 24x7 Operations Support • Megawatt to Gigawatt Scale Services
Space - to - Earth	• Lunar Resource Model • Asteroidal Resource Model • Drive launch costs down to $100/kg to LEO • Atmospheric Transparency • Beam Management -- Frequency/Control/Security • MOCA Authentication, Authorization and Control System	• Modular Structure I/Fs (mechanical/robotic/ control/thermal) • Thermal Management • Pointing Large Structures • Electro-Magnetic/Optical Alignment • Solar Dynamic Modules • Non-Iridium Based Concentrated Photovoltaic	• Power & Ancillary Services Beaming to UAVs & Others • Power & Ancillary Services Beaming to Forward Bases • Power & Ancillary Services Beaming to Terrestrial Grid	• Synergistic impact of Cislunar Development • Dispatchable Power & Ancillary Services • National and International Geopolitical High Ground • Gigawatt to Terawatt Scale Services

CHALLENGES OF SPACE
POWER BEAMING & ANCILLARY SERVICES



Xtraordinary Innovative Space Partnerships, Inc

Power Density* versus the Solar Constant

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

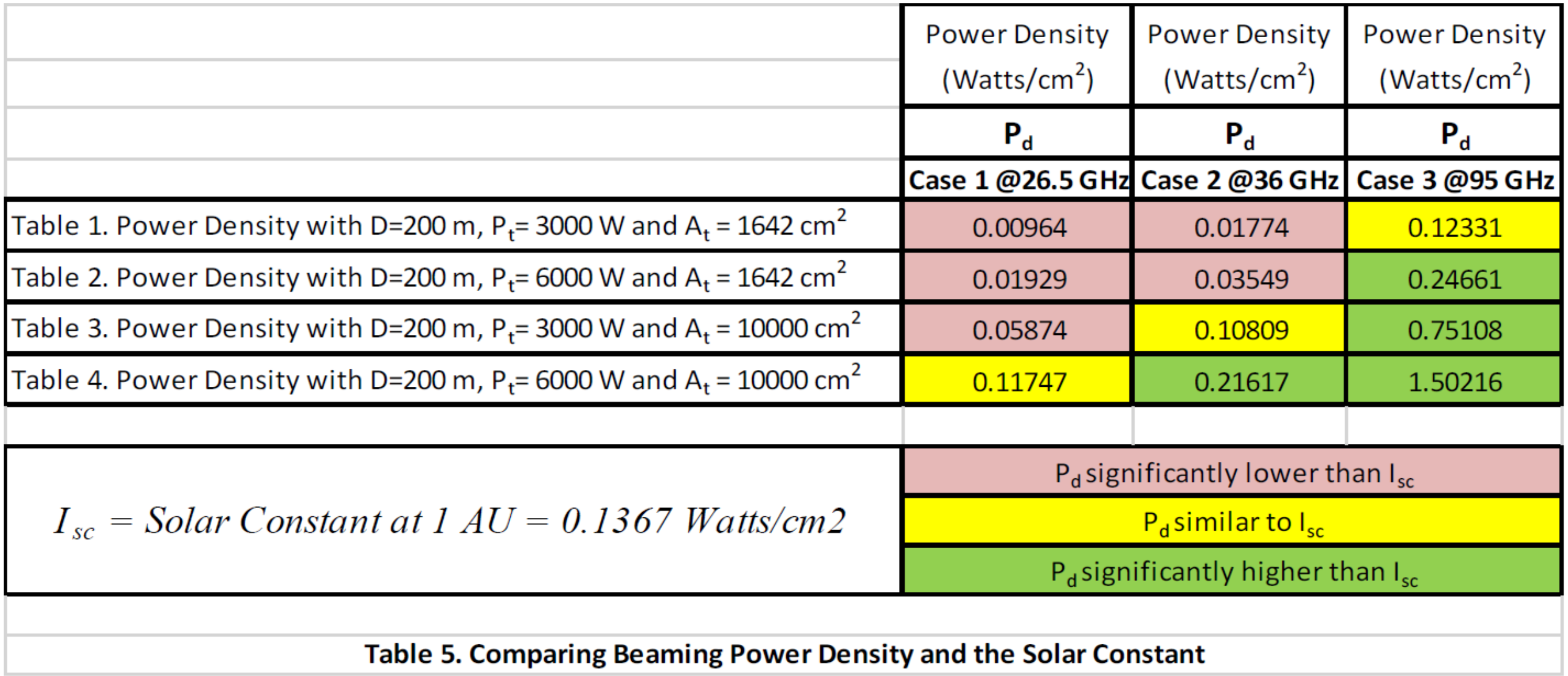
p_d is the power density at the center of the receiving location

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



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

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

P_d significantly lower than I_{sc}

P_d similar to I_{sc}

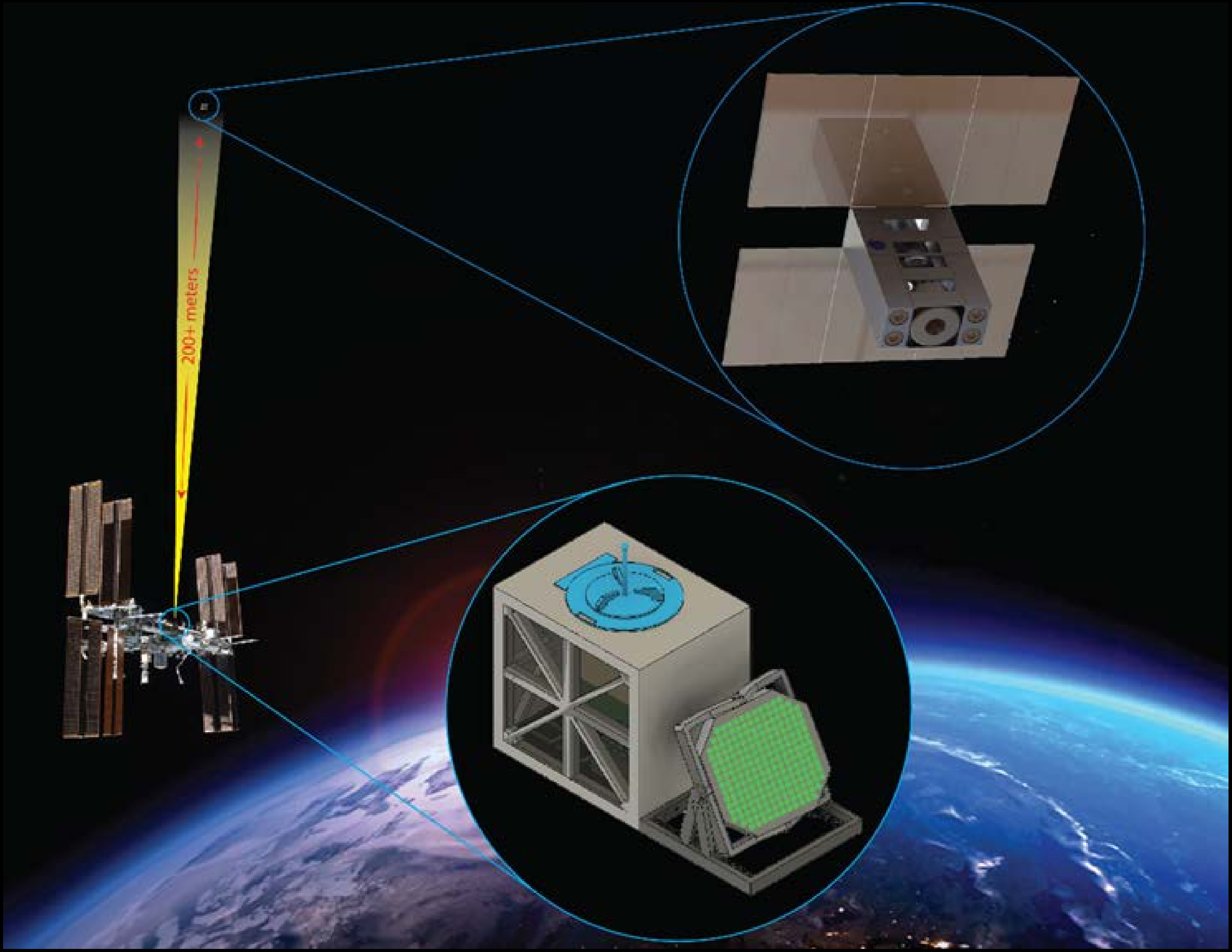
P_d significantly higher than I_{sc}

Table 5. Comparing Beaming Power Density and the Solar Constant

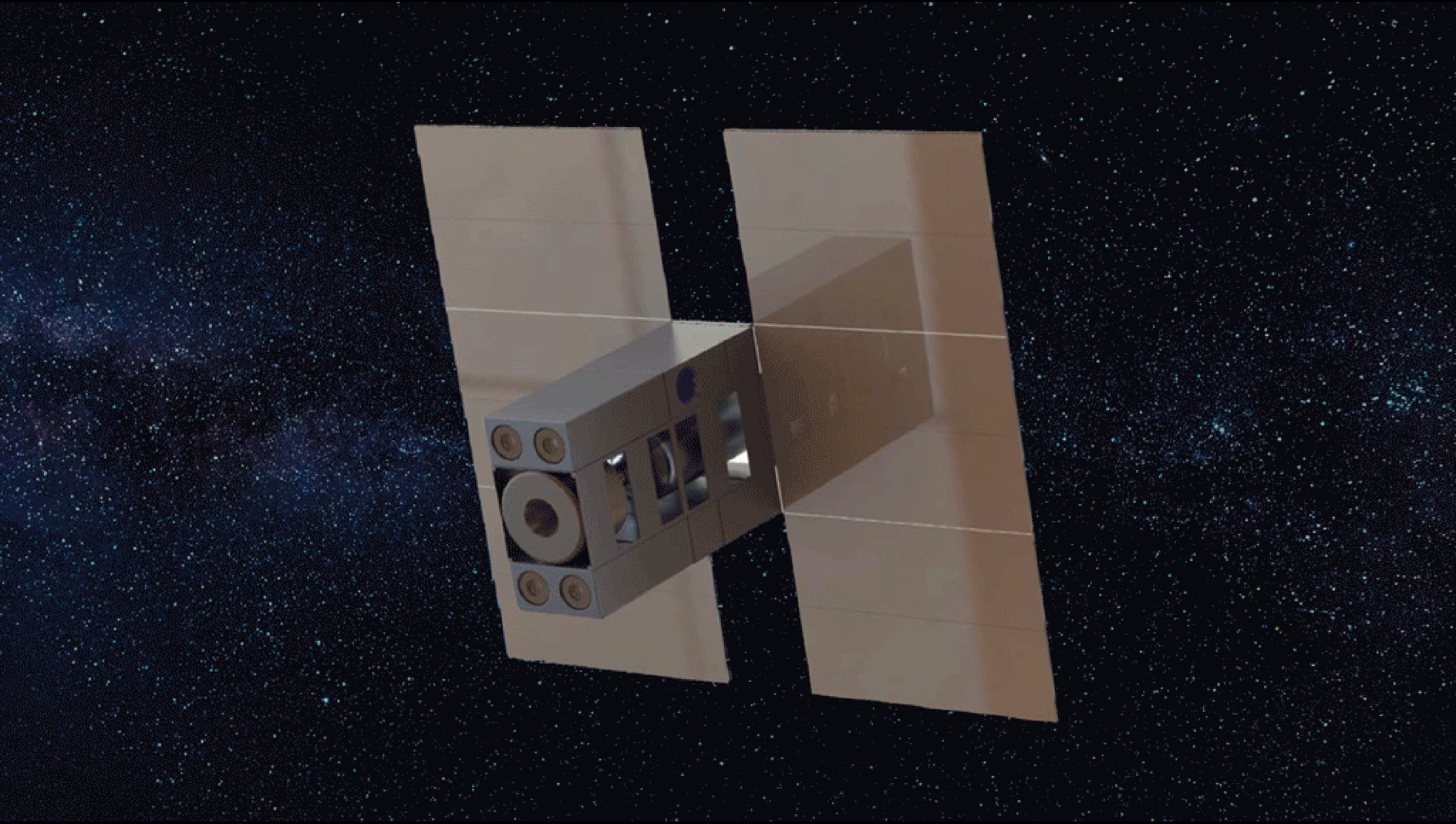
1 - Barnhard, Gary Pearce Space-to Space Power Beaming AIAA Space 2017

2 - 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

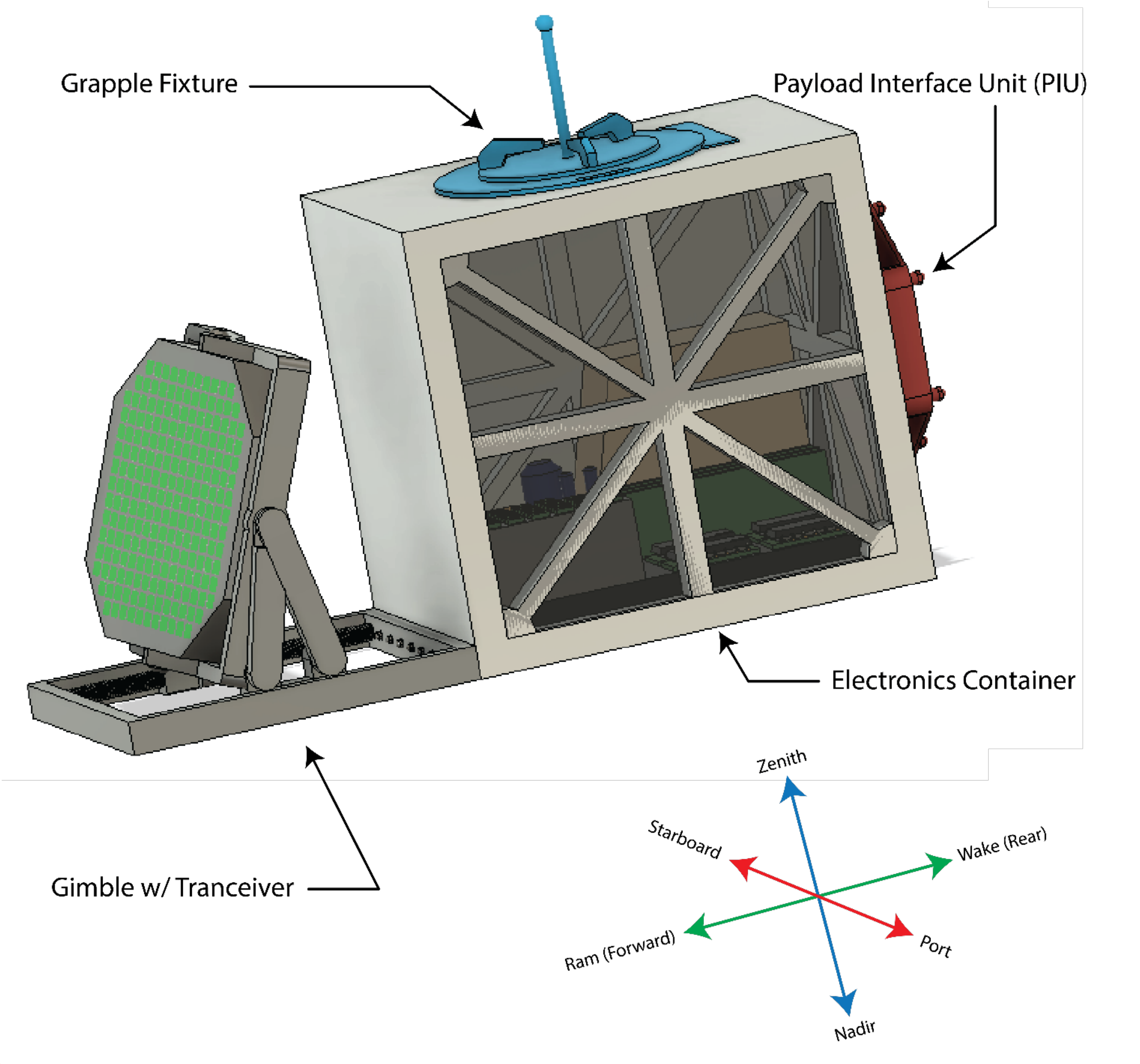
SSPB Mission Overview



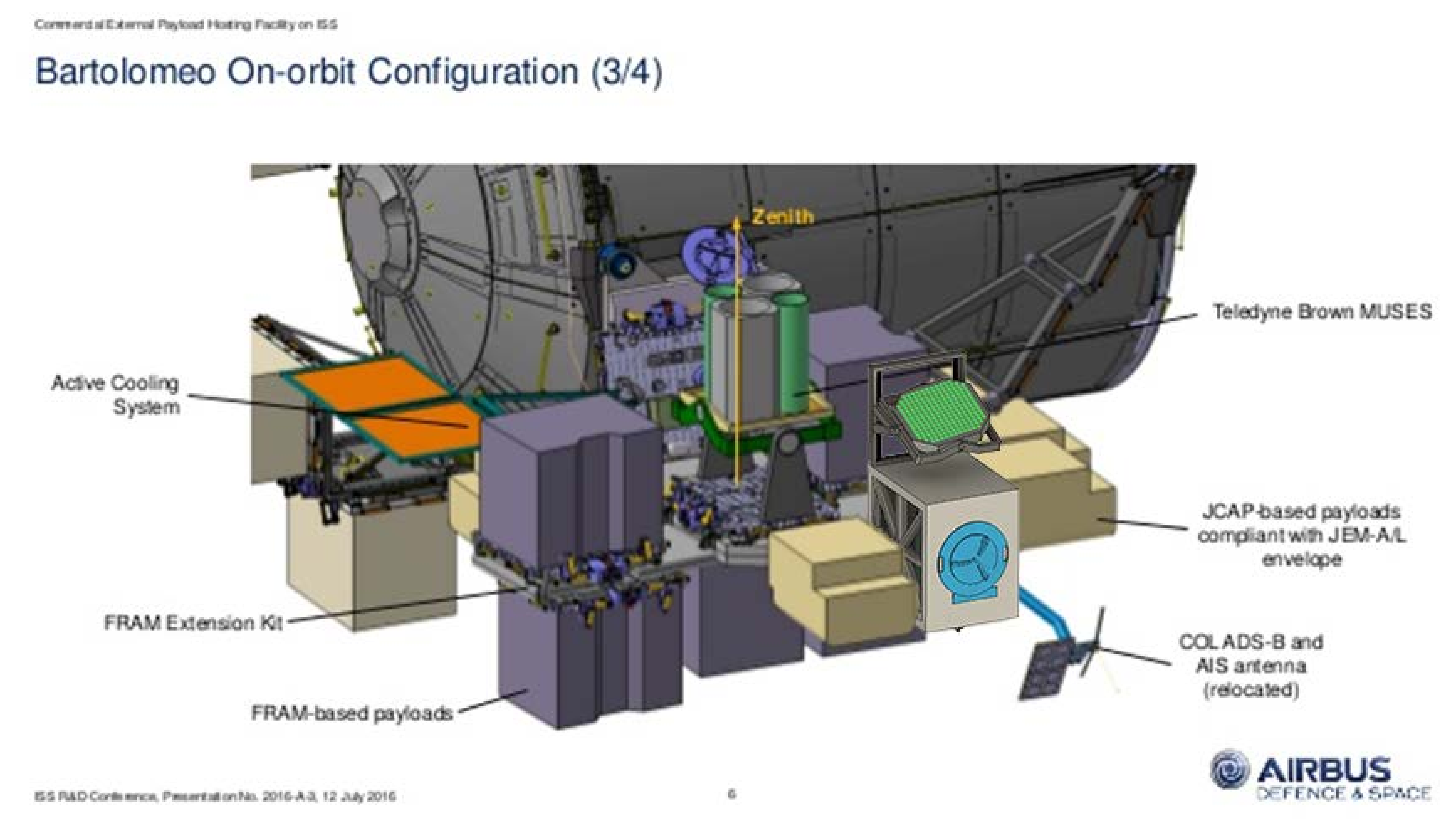
SSPB Mission Overview



SSPB Transceiver Preliminary Design Isometric



Barto Exposed Facility Accommodations



Commercial External Payload Hosting Facility on ISS

Bartolomeo On-orbit Configuration (3/4)

ISS R&D Conference, Presentation No. 2016-A-3, 12 July 2016

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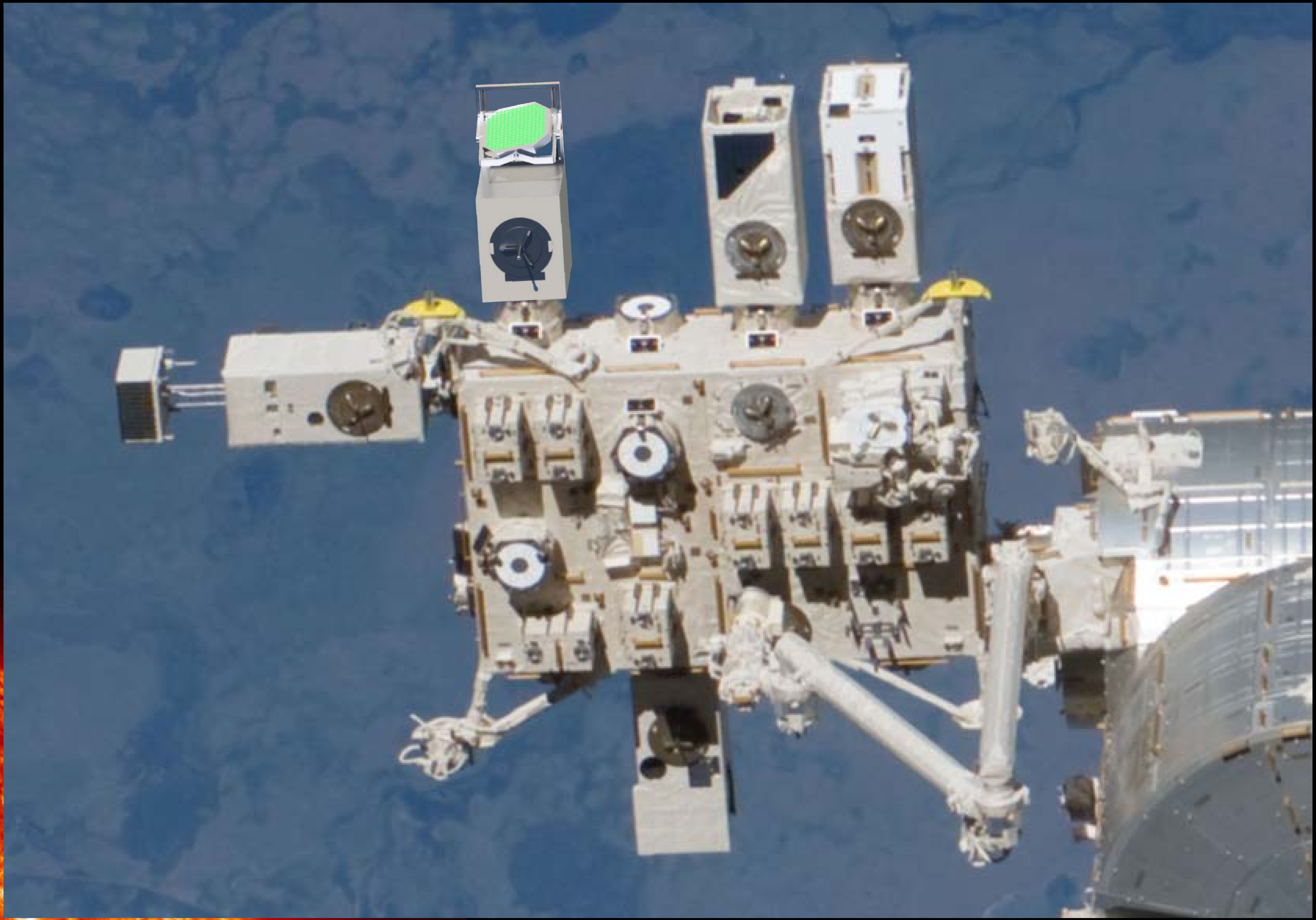
JEM Exposed Facility Accommodations

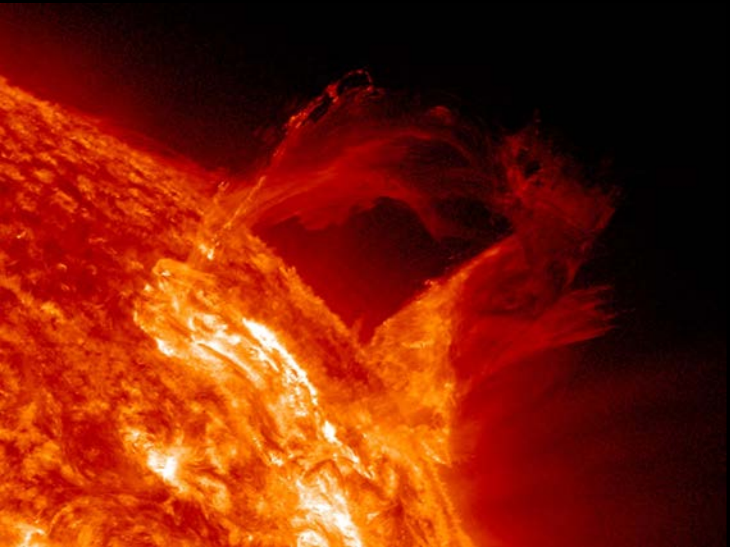


SSPB - Mission Overview

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

SSPB Phase I - Technology Development Components

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



SSPB Phase II - Technology Deployment Components

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

Cygnus & Dragon Free flyers

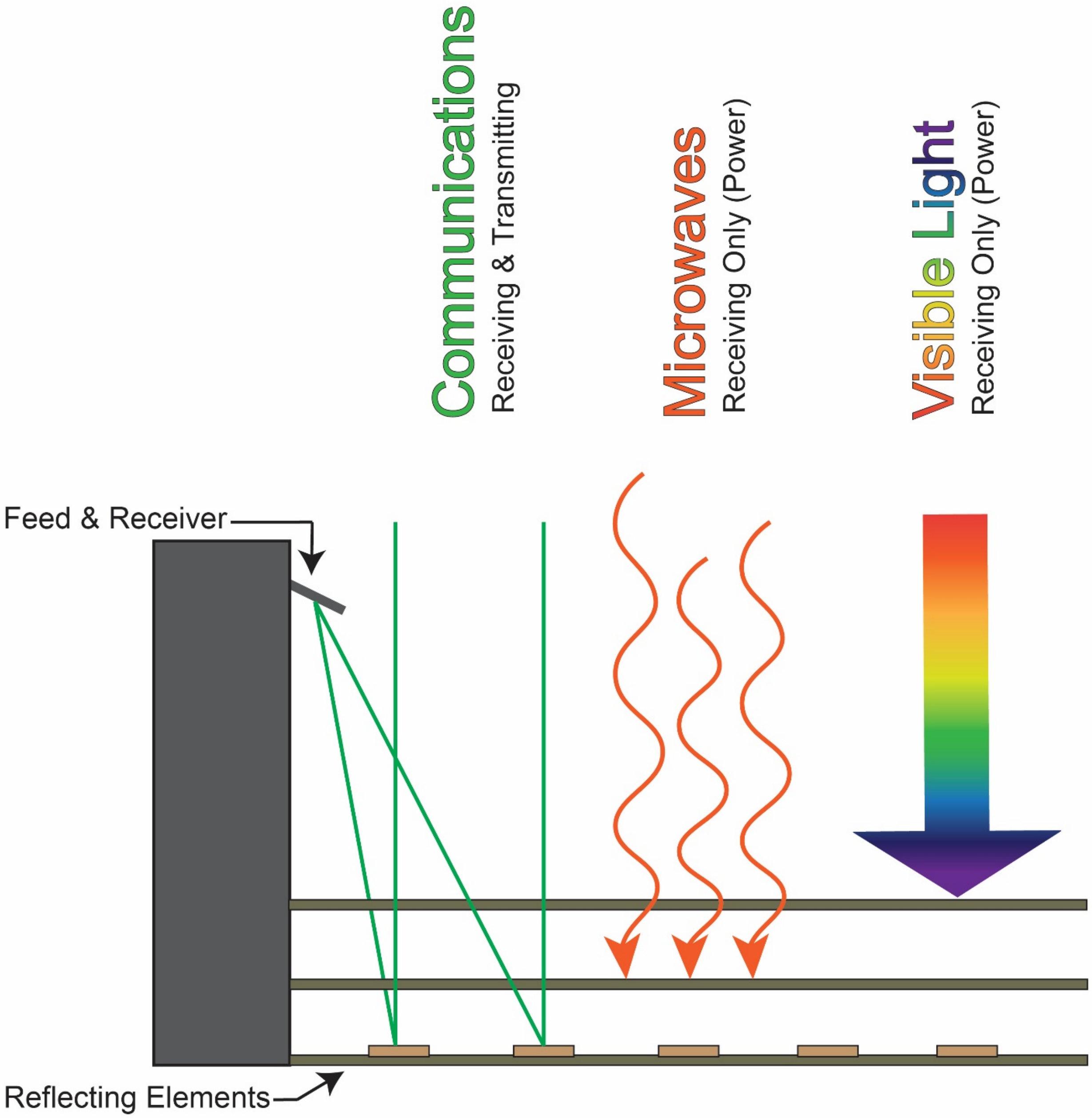
THE VALUE OF PERFORMANCE.
NORTHROP GRUMMAN

SPACEX

SSPB Phase III - Technology Deployment Components

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

  ➔Emergency ➔ Servicing ➔Augment ➔Backup ➔Primary.



Layer 1 - Solar Panel

Layer 2 - Rectenna

Layer 3 - Communications Reflector

Applications & Customers

- Commercial space beaming applications include:
  - Expansion of operational mission capabilities,
  - Power densities an order of magnitude above I_{sc}
  - Multiplexed power and ancillary services (e.g., comm, data, navigation, time → Situational Awareness)
  - Enhanced spacecraft/infrastructure design flexibility, and
  - out-bound orbital trajectory insertion propulsion, and
  - pave the way for the Lunar Power & Light Company.
- Government space applications include:
  - Sustainable, interoperable, high power generation, storage, and distribution
  - Frequency agnostic extension of cognitive software defined radios
  - Operational Flexibility + Situation Awareness = Enhanced Space Power

SSPB & Commercial On-Ramps

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

SSPB & Commercial Evolution

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

SSPB Test Bed Experiments

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

Where does it make sense to use the technology?

SSPB Mathematics & Efficiency

Technologies for wireless power transmission include:

- Microwave
- Laser
- Induction

Each of these methods vary with respect to:

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

SSPB Microwave Efficiency Data

DC to Microwave Conversion	Beam Forming Antenna	Free Space Transmission	Reception Conversion to DC
Circa 1992 80%–90% Efficient **Circa 2016** ~95 % Efficient** @ < 6 GHz 10%-60% @ Higher Freq.	**Circa 1992** 80 – 90 % Efficient **Circa 2016** Comparable @ < 6 GHz 50%-80% @ Higher Freq.	**Circa 1992** 80 – 90 % Efficient **Circa 2016** Comparable @ < 6 GHz 1%-90% @ Higher Freq.	**Circa 1992** 80 – 90 % Efficient **Circa 2016** ~95 % Efficient** @ < 6 GHz 37%-72% @ Higher Freq.

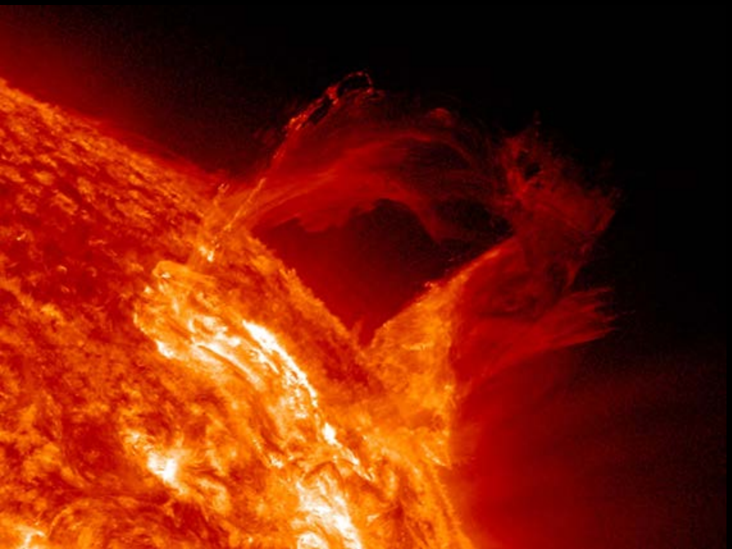
Theoretical Maximum Possible DC to DC Efficiency
Circa 1992 ~76%
Circa 2016 85-95%*** @ < 6 GHz and TBD @ Higher Frequencies
Experimental DC to DC Efficiency Circa 1992 ~54 %, Circa 2016 TBD but significantly higher

*William C. Brown, Life Fellow, IEEE, and E. Eugene Eves, Beamed Microwave Power Transmission and its Application to Space, IEEE Transactions On Microwave Theory and Techniques, Vol. 40, No. 6. June 1992
**depending on voltage multiplier ratio
***using one cycle modulation instead of pulse width modulation
Current High Frequency values based on input from current researchers (see paper for references)

SSPB Recent Fiber Laser Data

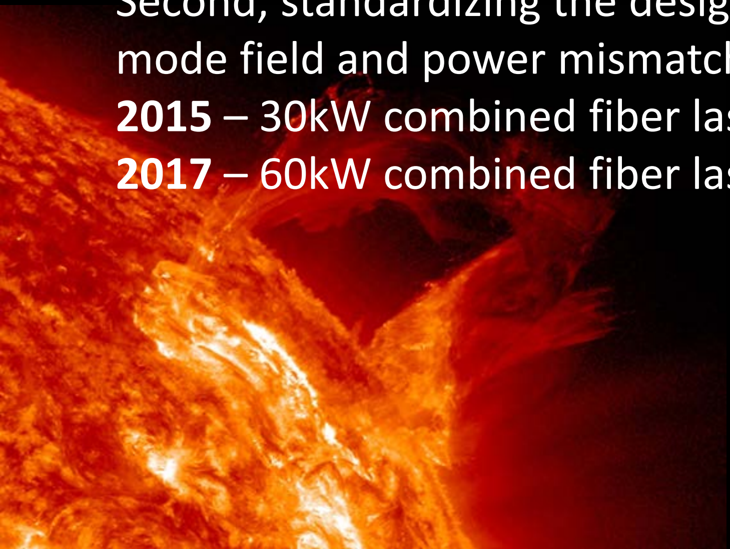
2013 – Propagation efficiencies of 90%, at 1.2km, 3kW CW – U.S. NRL
2013 – 10kW CW individual, single-mode, fiber lasers – U.S. NRL
2014 – 3kW three-fiber array, 80% efficiency – Northrop Grumman
2015 – 30kW combined fiber laser mobile system fielded – Lockheed Martin & U.S. Army
2017 – 60kW combined fiber laser mobile system fielded – Lockheed Martin & U.S. Army

Demonstrated source power to beam efficiency of 43 percent



SSPB Recent Fiber Laser Data

2013 – Propagation efficiencies of 90 percent, at a range of 1.2 kilometers (km), with transmitted continuous-wave power levels of 3 kilowatt (kW) – U.S. Naval Research Laboratory
2013 – 10kW individual, single-mode, fiber lasers continuous power – U.S. Naval Research Laboratory
2014 – Three-fiber array combining results, showing a constant 80% efficiency across a broad range of input powers (0–3000W). – Northrup Grumman Two straightforward changes appear likely to increase the combining efficiency from 80% to 90% or more. First, combining more fibers increases Diffractive Optical Element (DOE) diffraction efficiency, leading to greater combining efficiency as well as higher combined power. We successfully fabricated DOEs with fiber channel counts ranging from 9–81, leading to diffraction efficiencies of 97–99%, compared with only 92% for our three-fiber DOE. Second, standardizing the design of the fiber amplifiers would reduce losses arising from mode field and power mismatches and should also be relatively simple.
2015 – 30kW combined fiber laser mobile system fielded – Lockheed Martin & U.S. Army
2017 – 60kW combined fiber laser mobile system fielded – Lockheed Martin & U.S. Army

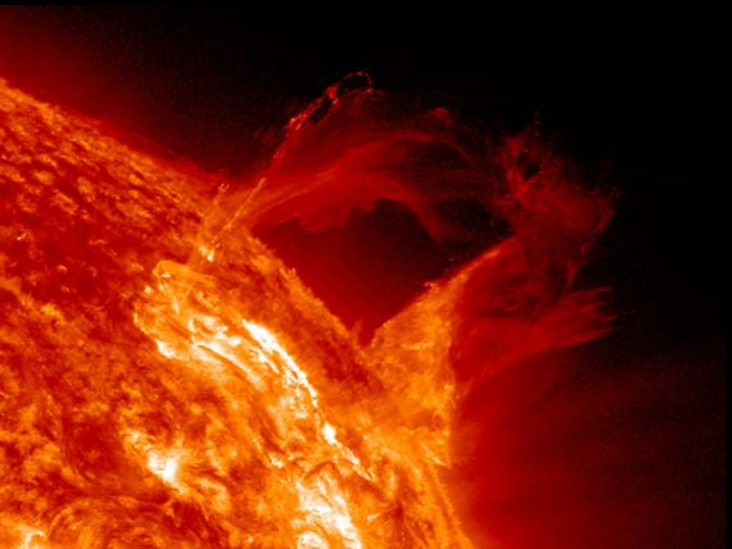


Demonstrated source power to beam efficiency of 43 percent

SSPB Mathematics & Efficiency

Theoretical Limits & Other Considerations

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



Mathematics of Power Beaming* - Power Density

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

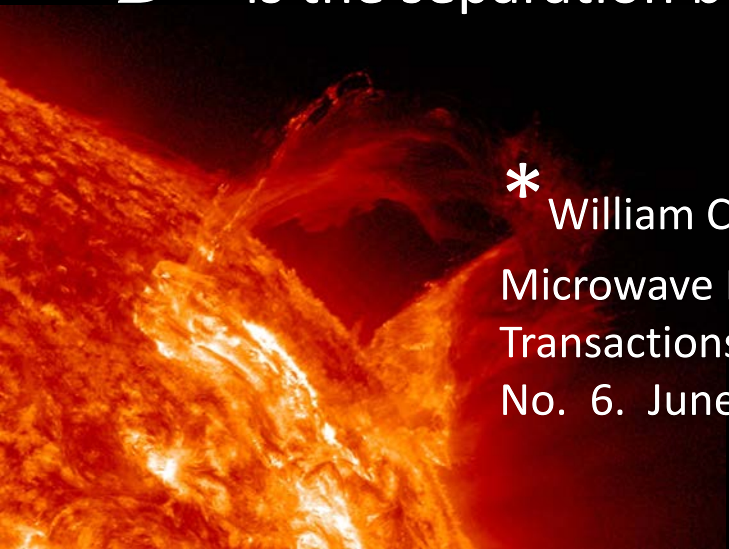
p_d is the power density at the center of the receiving location

P_t is the total radiated power from the transmitter

A_t is the total area of the transmitting antenna

λ^2 is the wavelength squared

D^2 is the separation between the apertures squared

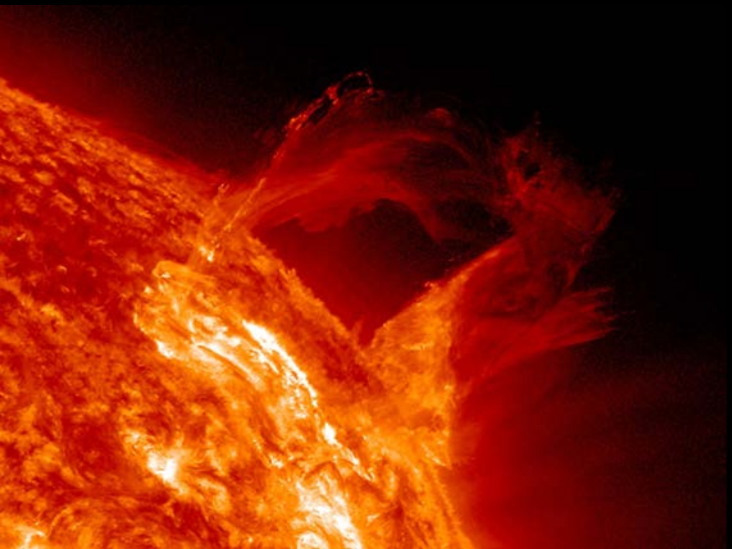


*William C. Brown, Life Fellow, IEEE, and E. Eugene Eves, Beamed Microwave Power Transmission and its Application to Space, IEEE Transactions On Microwave Theory and Techniques, Vol. 40, No. 6. June 1992

Mathematics of Power Beaming* - Power Received

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

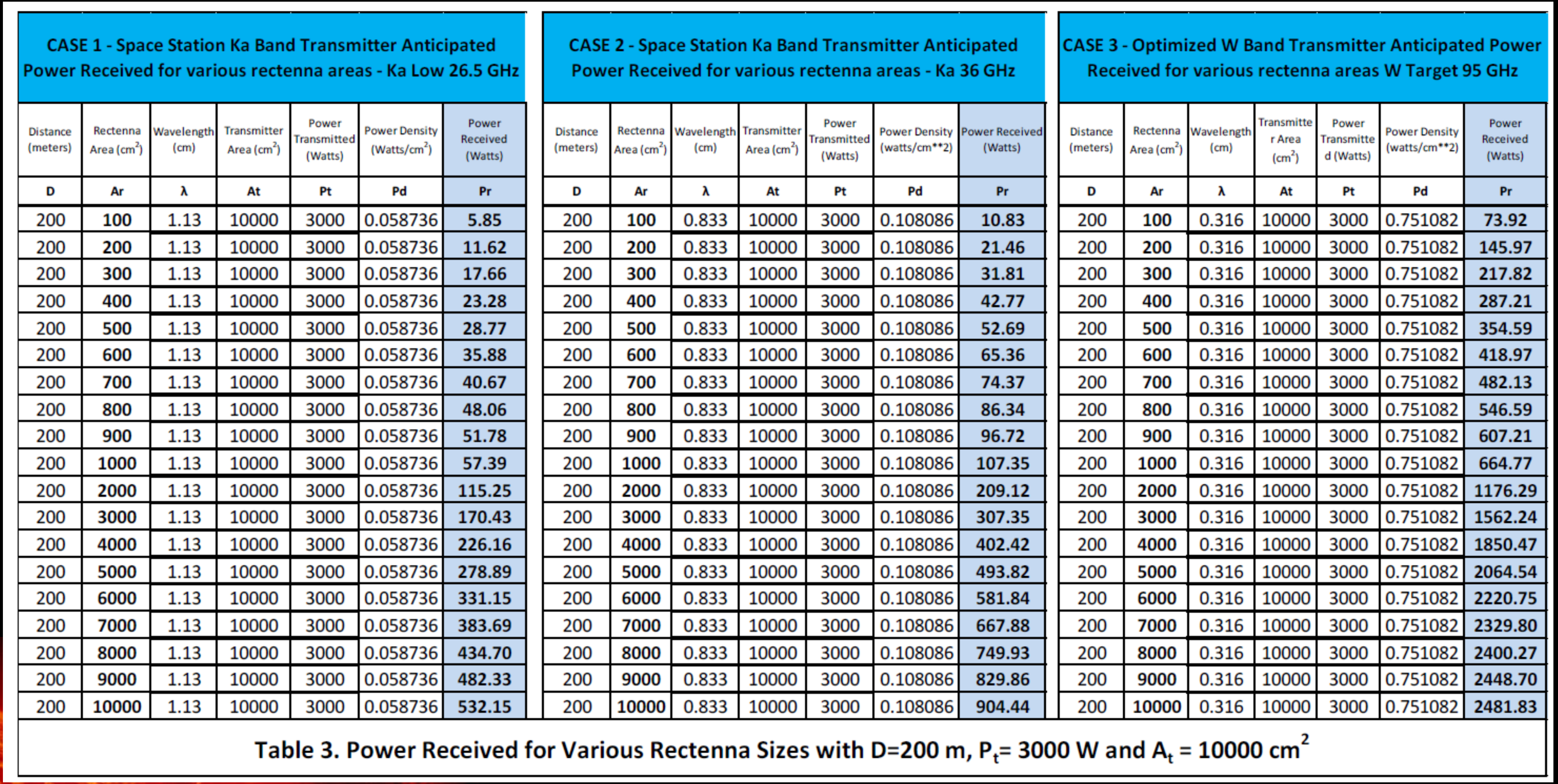
Accordingly, the Pr is calculated using the collection efficiency method instead of the far-field equations.



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

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

Power Density* - More Optimal Solutions



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

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

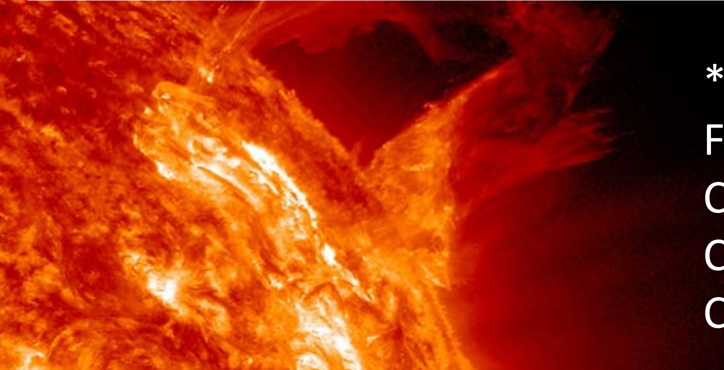
CASE 2 - Space Station Ka Band Transmitter Anticipated Power Received for various rectenna areas - Ka 36 GHz

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

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

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

Table 3. Power Received for Various Rectenna Sizes with D=200 m, P_t= 3000 W and A_t = 10000 cm^2



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

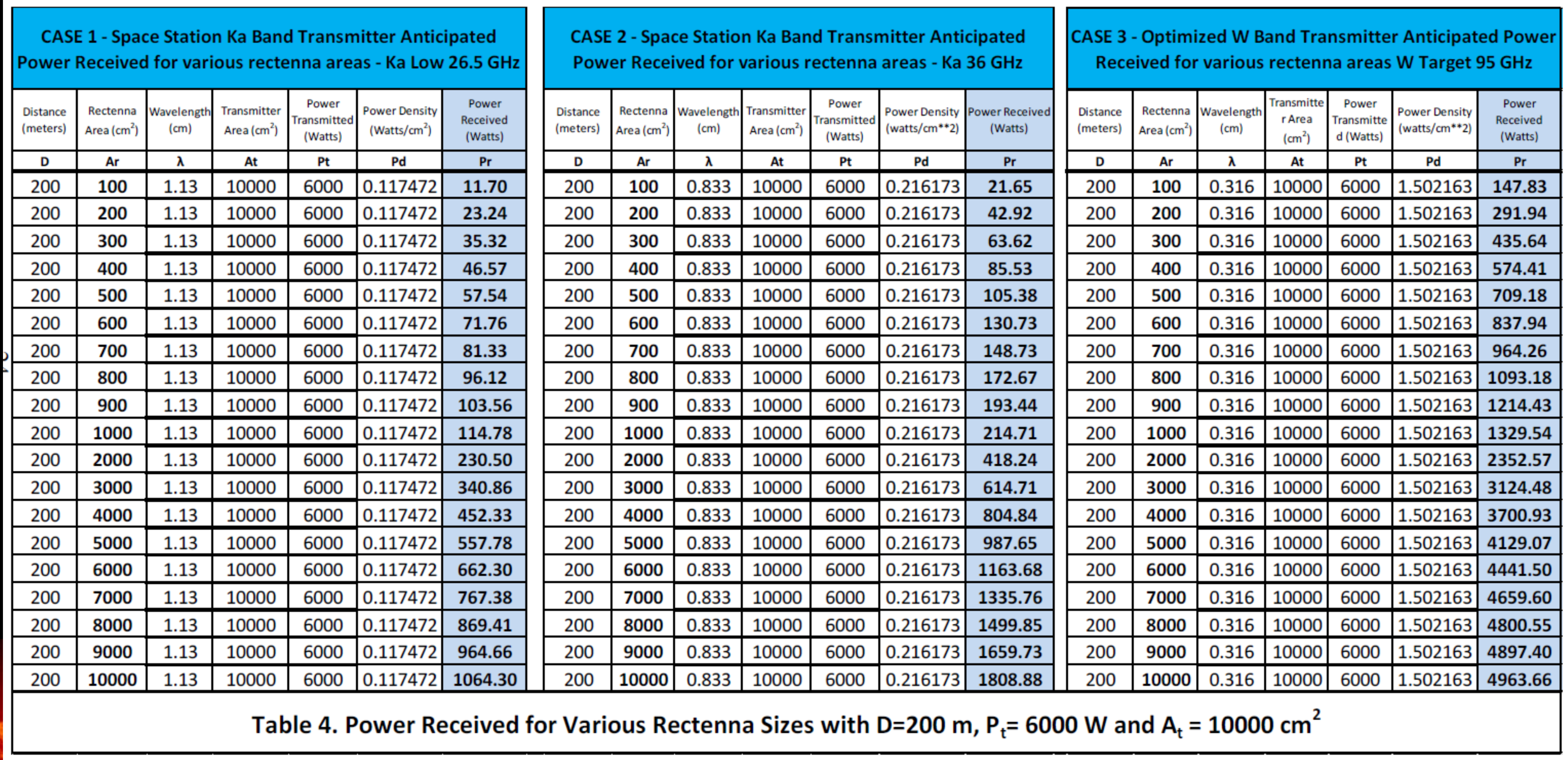
For rectennas ranging from 100 cm^2 to 10000 cm^2

Case 1 frequency = 26.5 GHz ➔ λ = 1.13 cm

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

Case 3 frequency = 95.0 GHz ➔ λ = 0.316 cm

Power Density* - More Optimal Solutions



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

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

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

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

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

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

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

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

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

Case 1 frequency = 26.5 GHz ➔ λ = 1.13 cm

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

Case 3 frequency = 95.0 GHz ➔ λ = 0.316 cm

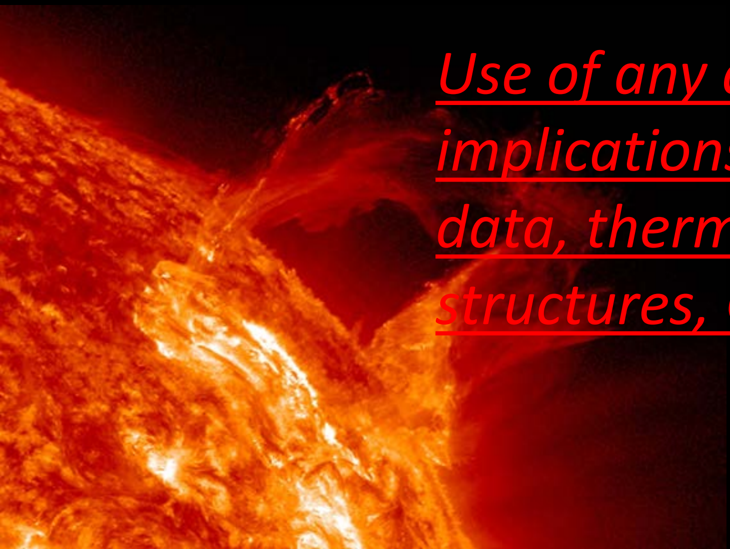
Technological Challenges

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

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

Technological Challenges -2

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



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

Technological Challenges - 3

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

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

– Jan L.A. van de Snepscheut
computer scientist

Additional Challenges - 3

- Economics

– Map the financing to terrestrial electrical power and ancillary services utility analog that just happens to be in space.

– Each addressable market has different fundamental figures of merit.

- Public/Private Partnerships

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

- GeoPolictical

– Make International Cooperation/Collaboration real.

REPRESENTATIVE TIMELINE

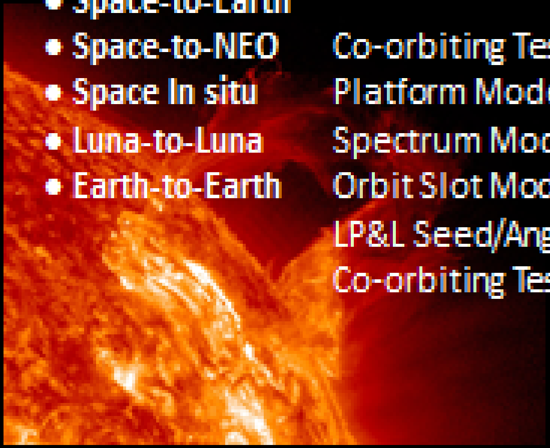
Energy TD^3 Iterative and Recursive Milestones

Technology Development → Technology Demonstration → Technology Deployment

Space Solar Power

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

2019	2022	2025	2029	2038	2047
ISS TD^3	LEO TD^3	GEO TD^3	GEO TD^3	GEO TD^3	SSP's >
3-6 KW	~100 KW	~100 MW	~2 GW	10 GW	50 GW
SSP Testbed	SSP LEO Demo	SSP GEO Demo	Full SSP		
NASA/DOD	NASA/DOD/DOE	NASA/DOD/DOE	Electrical Utility		
Commercial	Commercial	Commercial	Commercial		
Co-orbiting Test	ComSats Recovery	ComSats Primary	→ $$$	→ $$$$	
Platform Model	Platform TD^3	Platform Ops	→ $$$	→ $$$$	
Spectrum Model	Spectrum Apply	Spectrum Allocation			
Orbit Slot Model	Orbit Slot Apply	Orbit Slot Allocation			
LP&L Seed/Angel	LP&L Series A/B/C	LP&L IPO	→ $$$	→ $$$$	
Co-orbiting Tests	Co-orbiting Labs	Co-orbiting Facilities	→ $$$	→ $$$$	
	Lunar Test(s)	Lunar Operations	→ $$$	→ $$$$	
	NEO Test(s)	Asteroidal Assay	→ $$$	→ $$$$	



Next Steps

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

Conclusion

- SSPB has transitioned from a conceptual mission pregnant with opportunity to a commercial mission with recognized standing.
- There is now a defined confluence of interests biased toward successful execution of the mission as Public Private Partnership.
- Successful demonstration of space solar power beaming will:
  1. Reduce the perceived cost, schedule, technical risk of SSP
  2. Pave the way for SSP use in multiple venues
     space-to-space, surface-to-surface, space-to-lunar/infrastructure surface, and space-to-Earth

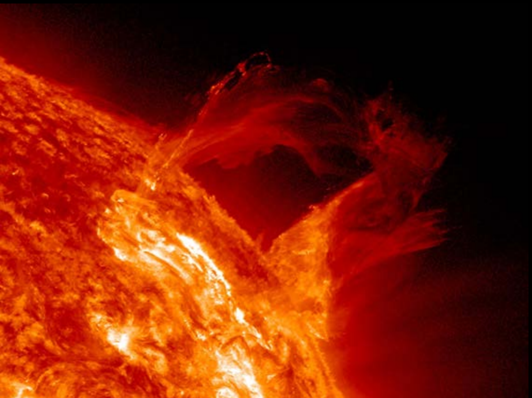
Don’t wait for the future, help us make it!

Surface-to-Surface SSPB (1 of 2)

- *The ability to provide power and ancillary services when and where needed is essential to virtually all aspects of human endeavor* and enables all forms of space exploration, development, and settlement.
- *Defining an incremental path* to realize the necessary power infrastructure to support settlement and its precursor activities is a significant systems engineering challenge.
- It is necessary to determine *what are the increments of scalable interoperable modular power and ancillary services* needed to support exploration, prospecting, proving reserves, exploitation, habitation, and settlement of the lunar surface, as well as how the requirements for the same can be accommodated.
- *Each increment must provide the necessary power and services needed to construct the next increment* in a timely manner, given system lifetime and financial constraints

Surface-to-Surface SSPB (2 of 2)

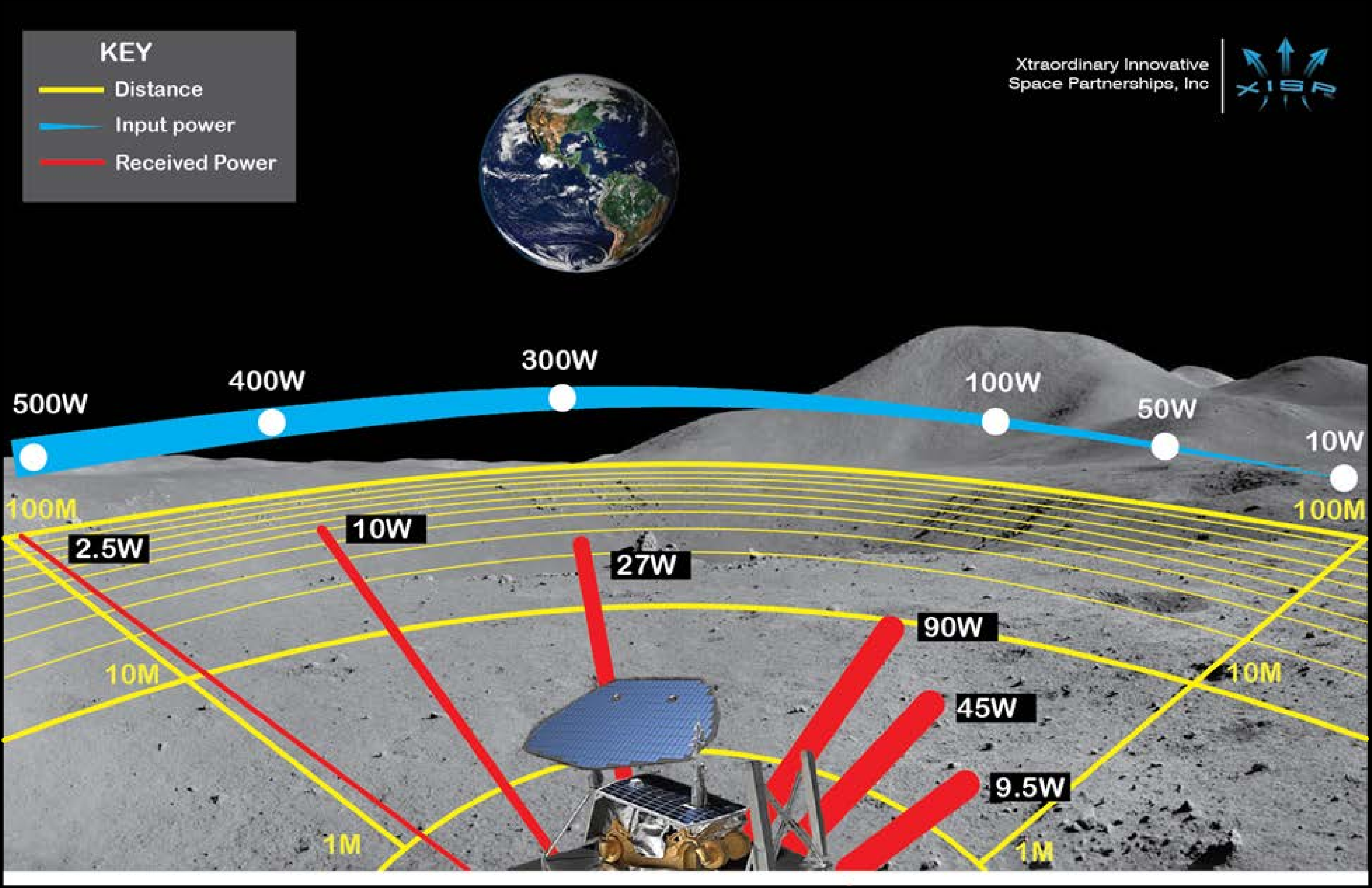
- *The current state-of-the-art with respect to surviving and operating through the night on the lunar surface is profoundly limited*.
- While *there are multiple terrestrial and even space qualified technologies* that could be leveraged to design viable end-to-end power generation, storage, and distribution systems suitable for the lunar environment, *the systems engineering of the same is nascent*.
- This work seeks to establish a *framework for curating/generating, intersecting, and converging multiple technology development efforts* to yield a recommended set of deployable power and ancillary services beaming infrastructure payloads.



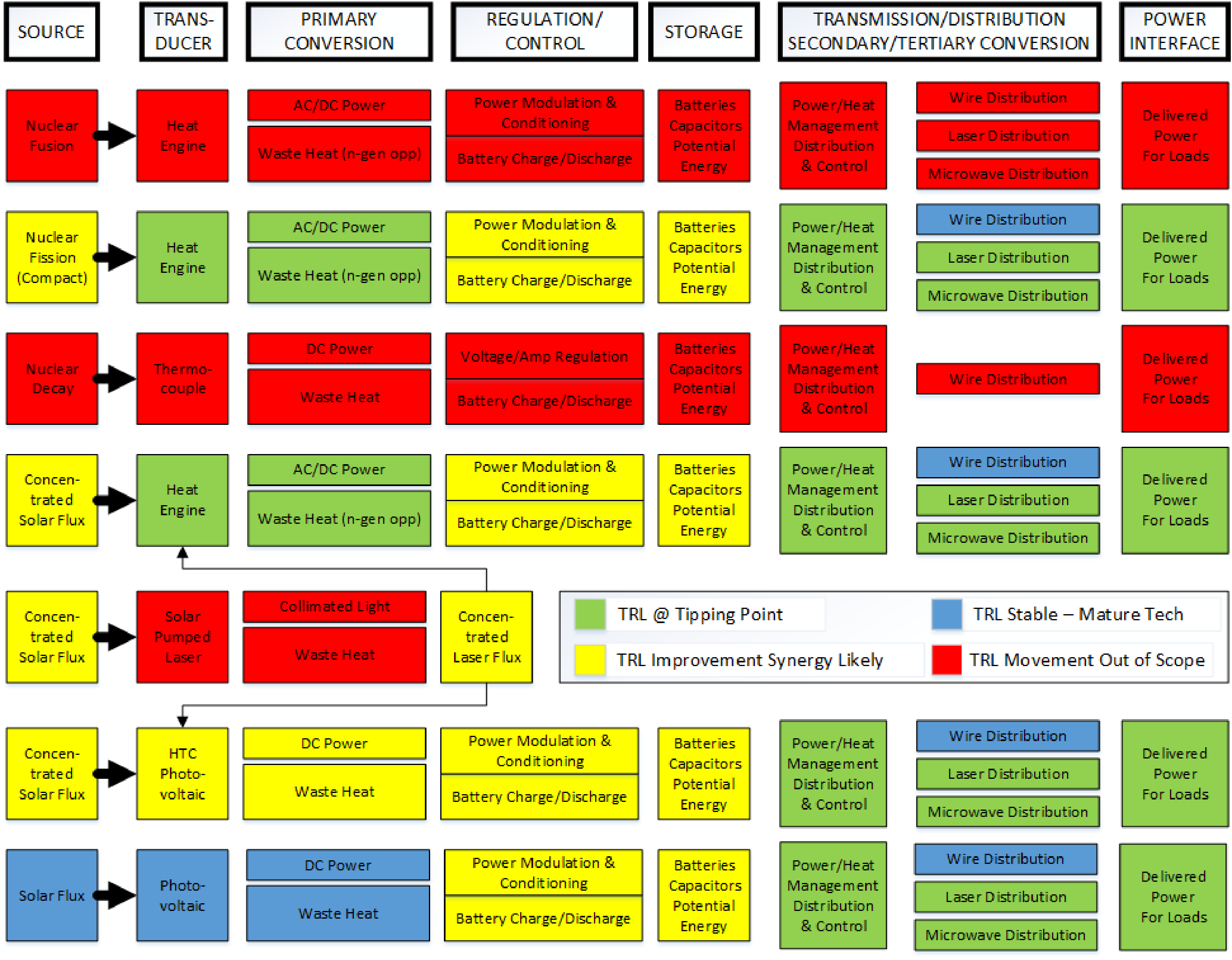
Surface-to-Surface Power Beaming

CLPS 15 Kg Power Beaming Testbed

XISP-Inc/Raytheon Proposal submitted for SMD LSITP 2019



Problem Space Block Diagram End-to-End Power Systems



SOURCE	TRANS-DUCER	PRIMARY CONVERSION	REGULATION/ CONTROL	STORAGE	TRANSMISSION/DISTRIBUTION SECONDARY/TERTIARY CONVERSION		POWER INTERFACE
🟥 Nuclear Fusion	🟥 Heat Engine	🟥 AC/DC Power 🟥 Waste Heat (n-gen opp)	🟥 Power Modulation & Conditioning 🟥 Battery Charge/Discharge	🟥 Batteries Capacitors Potential Energy	🟥 Power/Heat Management Distribution & Control	🟥 Wire Distribution 🟥 Laser Distribution 🟥 Microwave Distribution	🟥 Delivered Power For Loads
🟨 Nuclear Fission (Compact)	🟩 Heat Engine	🟩 AC/DC Power 🟩 Waste Heat (n-gen opp)	🟨 Power Modulation & Conditioning 🟨 Battery Charge/Discharge	🟨 Batteries Capacitors Potential Energy	🟩 Power/Heat Management Distribution & Control	🟦 Wire Distribution 🟩 Laser Distribution 🟩 Microwave Distribution	🟩 Delivered Power For Loads
🟥 Nuclear Decay	🟥 Thermo-couple	🟥 DC Power 🟥 Waste Heat	🟥 Voltage/Amp Regulation 🟥 Battery Charge/Discharge	🟥 Batteries Capacitors Potential Energy	🟥 Power/Heat Management Distribution & Control	🟥 Wire Distribution	🟥 Delivered Power For Loads
🟨 Concen-trated Solar Flux	🟩 Heat Engine	🟩 AC/DC Power 🟩 Waste Heat (n-gen opp)	🟨 Power Modulation & Conditioning 🟨 Battery Charge/Discharge	🟨 Batteries Capacitors Potential Energy	🟩 Power/Heat Management Distribution & Control	🟦 Wire Distribution 🟩 Laser Distribution 🟩 Microwave Distribution	🟩 Delivered Power For Loads
🟨 Concen-trated Solar Flux	🟥 Solar Pumped Laser	🟥 Collimated Light 🟥 Waste Heat	🟨 Concen-trated Laser Flux				
🟨 Concen-trated Solar Flux	🟨 HTC Photo-voltaic	🟨 DC Power 🟨 Waste Heat	🟨 Power Modulation & Conditioning 🟨 Battery Charge/Discharge	🟨 Batteries Capacitors Potential Energy	🟩 Power/Heat Management Distribution & Control	🟦 Wire Distribution 🟩 Laser Distribution 🟩 Microwave Distribution	🟩 Delivered Power For Loads
🟦 Solar Flux	🟦 Photo-voltaic	🟦 DC Power 🟦 Waste Heat	🟨 Power Modulation & Conditioning 🟨 Battery Charge/Discharge	🟨 Batteries Capacitors Potential Energy	🟩 Power/Heat Management Distribution & Control	🟦 Wire Distribution 🟩 Laser Distribution 🟩 Microwave Distribution	🟩 Delivered Power For Loads

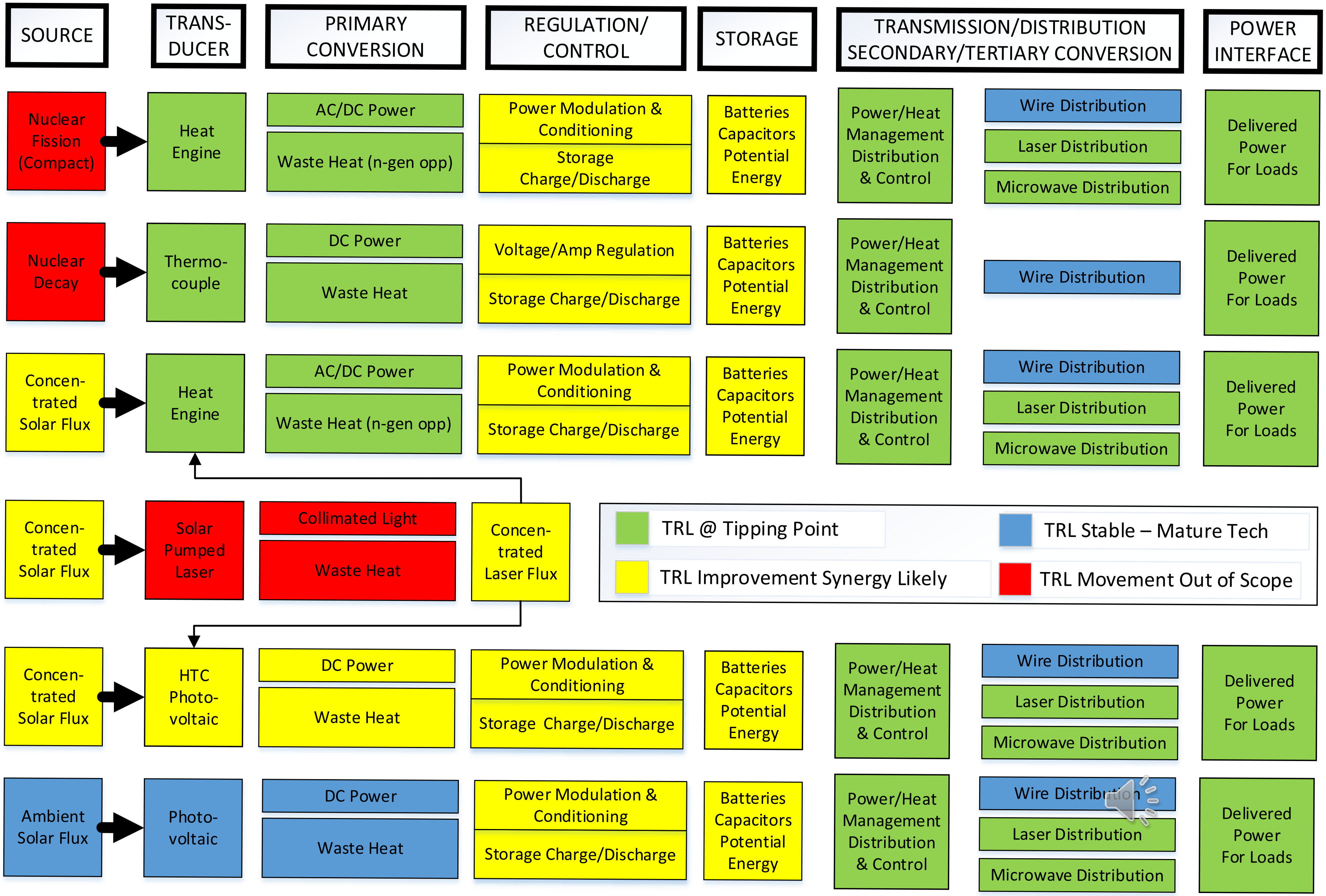
🟩 TRL @ Tipping Point

🟦 TRL Stable – Mature Tech

🟨 TRL Improvement Synergy Likely

🟥 TRL Movement Out of Scope

Trade Space: Power Generation, Storage, and Distribution



SOURCE	TRANSDUCER	PRIMARY CONVERSION	REGULATION/ CONTROL	STORAGE	TRANSMISSION/DISTRIBUTION SECONDARY/TERTIARY CONVERSION		POWER INTERFACE
🟥 Nuclear Fission (Compact)	🟩 Heat Engine	🟩 AC/DC Power 🟩 Waste Heat (n-gen opp)	🟨 Power Modulation & Conditioning 🟨 Storage Charge/Discharge	🟨 Batteries Capacitors Potential Energy	🟩 Power/Heat Management Distribution & Control	🟦 Wire Distribution 🟩 Laser Distribution 🟩 Microwave Distribution	🟩 Delivered Power For Loads
🟥 Nuclear Decay	🟩 Thermocouple	🟩 DC Power 🟩 Waste Heat	🟨 Voltage/Amp Regulation 🟨 Storage Charge/Discharge	🟨 Batteries Capacitors Potential Energy	🟩 Power/Heat Management Distribution & Control	🟦 Wire Distribution	🟩 Delivered Power For Loads
🟨 Concentrated Solar Flux	🟩 Heat Engine	🟩 AC/DC Power 🟩 Waste Heat (n-gen opp)	🟨 Power Modulation & Conditioning 🟨 Storage Charge/Discharge	🟨 Batteries Capacitors Potential Energy	🟩 Power/Heat Management Distribution & Control	🟦 Wire Distribution 🟩 Laser Distribution 🟩 Microwave Distribution	🟩 Delivered Power For Loads
🟨 Concentrated Solar Flux	🟥 Solar Pumped Laser	🟥 Collimated Light 🟥 Waste Heat	🟨 Concentrated Laser Flux				
🟨 Concentrated Solar Flux	🟨 HTC Photovoltaic	🟨 DC Power 🟨 Waste Heat	🟨 Power Modulation & Conditioning 🟨 Storage Charge/Discharge	🟨 Batteries Capacitors Potential Energy	🟩 Power/Heat Management Distribution & Control	🟦 Wire Distribution 🟩 Laser Distribution 🟩 Microwave Distribution	🟩 Delivered Power For Loads
🟦 Ambient Solar Flux	🟦 Photovoltaic	🟦 DC Power 🟦 Waste Heat	🟨 Power Modulation & Conditioning 🟨 Storage Charge/Discharge	🟨 Batteries Capacitors Potential Energy	🟩 Power/Heat Management Distribution & Control	🟦 Wire Distribution 🟩 Laser Distribution 🟩 Microwave Distribution	🟩 Delivered Power For Loads

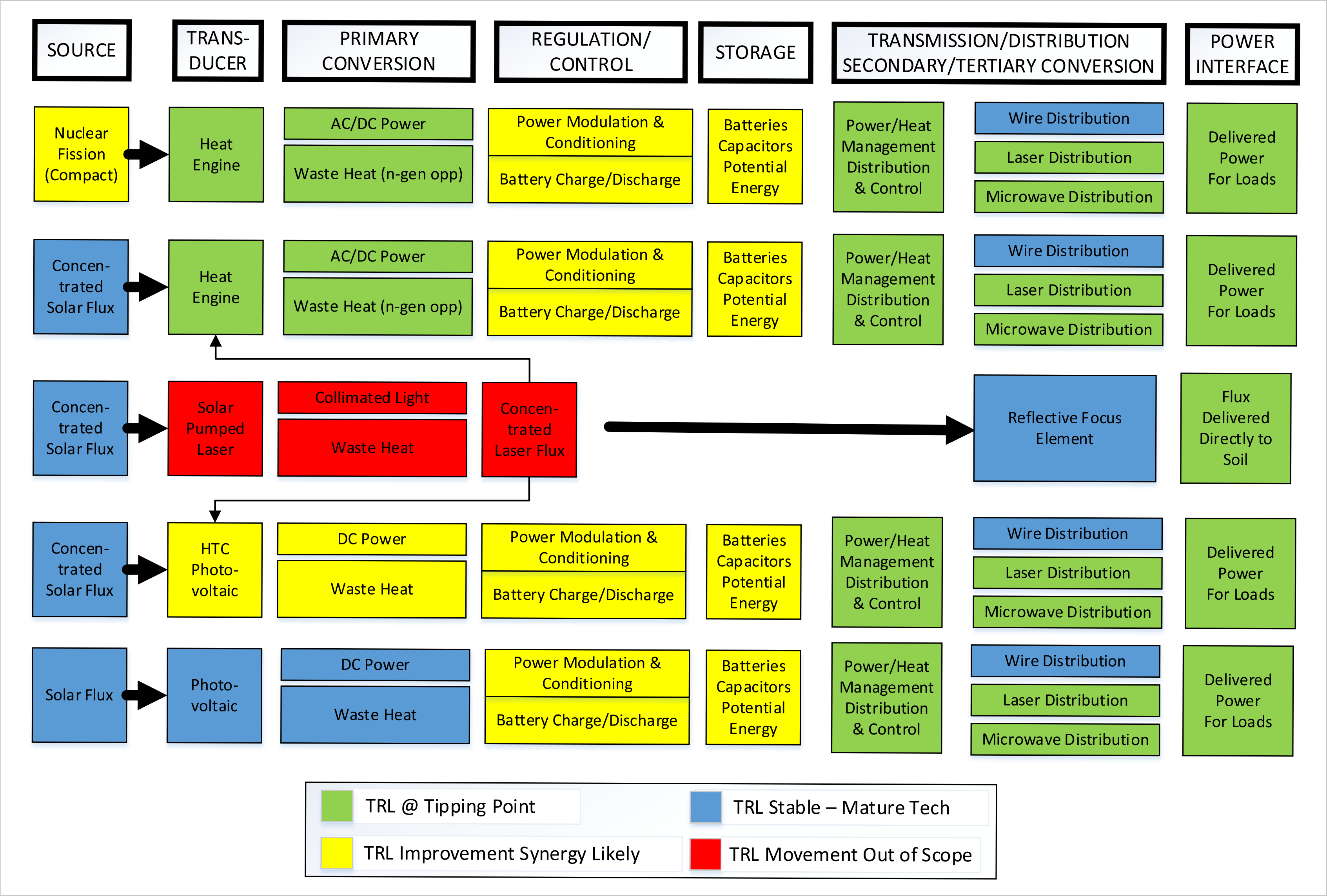
🟩 TRL @ Tipping Point

🟦 TRL Stable – Mature Tech

🟨 TRL Improvement Synergy Likely

🟥 TRL Movement Out of Scope

Sustainable Power Generation, Storage, and Distribution



SOURCE	TRANSDUCER	PRIMARY CONVERSION	REGULATION/ CONTROL	STORAGE	TRANSMISSION/DISTRIBUTION SECONDARY/TERTIARY CONVERSION		POWER INTERFACE
Nuclear Fission (Compact)	Heat Engine	AC/DC Power Waste Heat (n-gen opp)	Power Modulation & Conditioning Battery Charge/Discharge	Batteries Capacitors Potential Energy	Power/Heat Management Distribution & Control	Wire Distribution Laser Distribution Microwave Distribution	Delivered Power For Loads
Concentrated Solar Flux	Heat Engine	AC/DC Power Waste Heat (n-gen opp)	Power Modulation & Conditioning Battery Charge/Discharge	Batteries Capacitors Potential Energy	Power/Heat Management Distribution & Control	Wire Distribution Laser Distribution Microwave Distribution	Delivered Power For Loads
Concentrated Solar Flux	Solar Pumped Laser	Collimated Light Waste Heat	Concentrated Laser Flux			Reflective Focus Element	Flux Delivered Directly to Soil
Concentrated Solar Flux	HTC Photovoltaic	DC Power Waste Heat	Power Modulation & Conditioning Battery Charge/Discharge	Batteries Capacitors Potential Energy	Power/Heat Management Distribution & Control	Wire Distribution Laser Distribution Microwave Distribution	Delivered Power For Loads
Solar Flux	Photovoltaic	DC Power Waste Heat	Power Modulation & Conditioning Battery Charge/Discharge	Batteries Capacitors Potential Energy	Power/Heat Management Distribution & Control	Wire Distribution Laser Distribution Microwave Distribution	Delivered Power For Loads

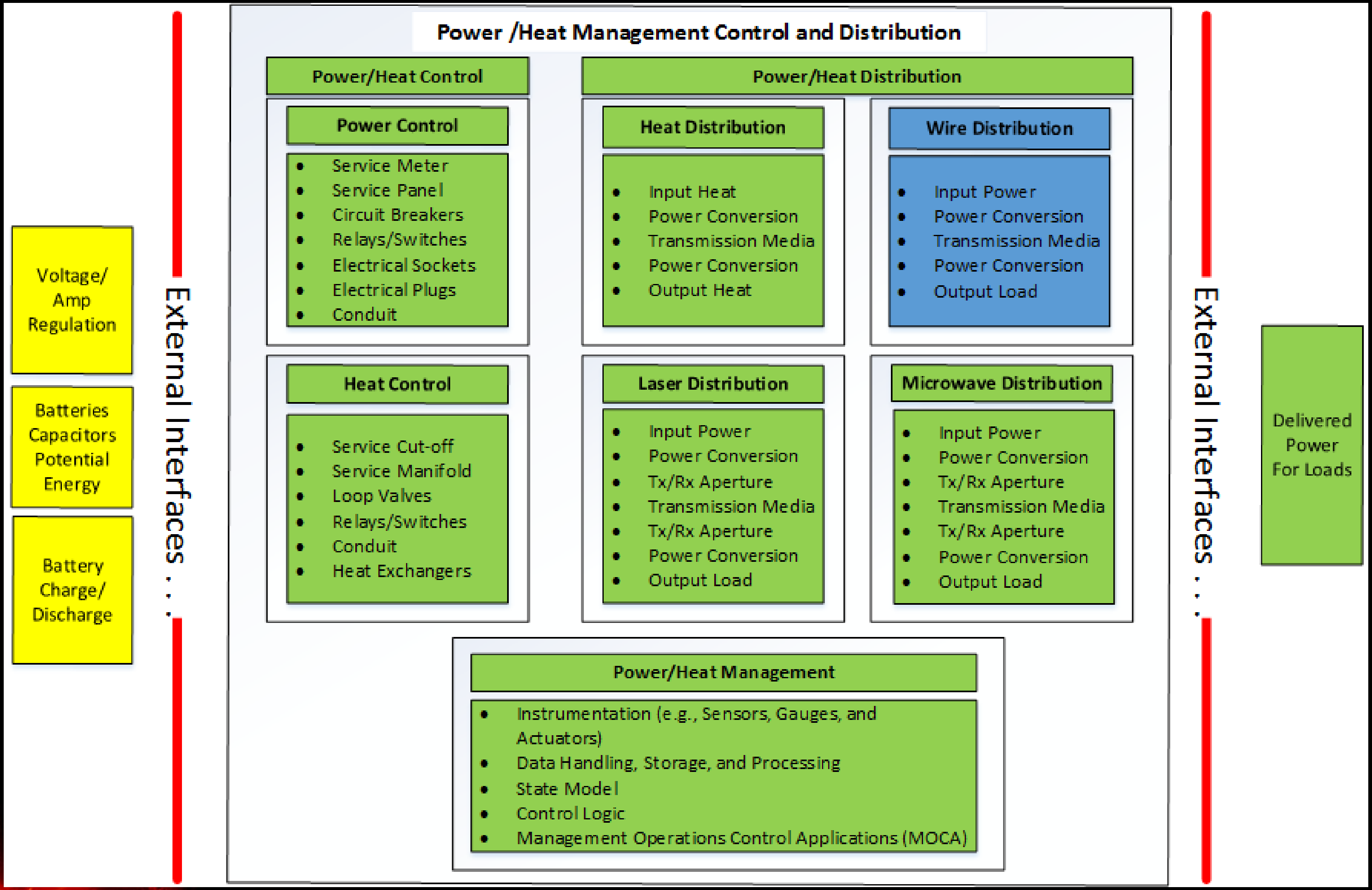
🟩 TRL @ Tipping Point

🟦 TRL Stable – Mature Tech

🟨 TRL Improvement Synergy Likely

🟥 TRL Movement Out of Scope

Power Distribution Interface Planes



Voltage/ Amp Regulation

Batteries Capacitors Potential Energy

Battery Charge/ Discharge

External Interfaces . . .

Power /Heat Management Control and Distribution

Power/Heat Control

Power Control

- Service Meter
- Service Panel
- Circuit Breakers
- Relays/Switches
- Electrical Sockets
- Electrical Plugs
- Conduit

Heat Control

- Service Cut-off
- Service Manifold
- Loop Valves
- Relays/Switches
- Conduit
- Heat Exchangers

Power/Heat Distribution

Heat Distribution

- Input Heat
- Power Conversion
- Transmission Media
- Power Conversion
- Output Heat

Wire Distribution

- Input Power
- Power Conversion
- Transmission Media
- Power Conversion
- Output Load

Laser Distribution

- Input Power
- Power Conversion
- Tx/Rx Aperture
- Transmission Media
- Tx/Rx Aperture
- Power Conversion
- Output Load

Microwave Distribution

- Input Power
- Power Conversion
- Tx/Rx Aperture
- Transmission Media
- Tx/Rx Aperture
- Power Conversion
- Output Load

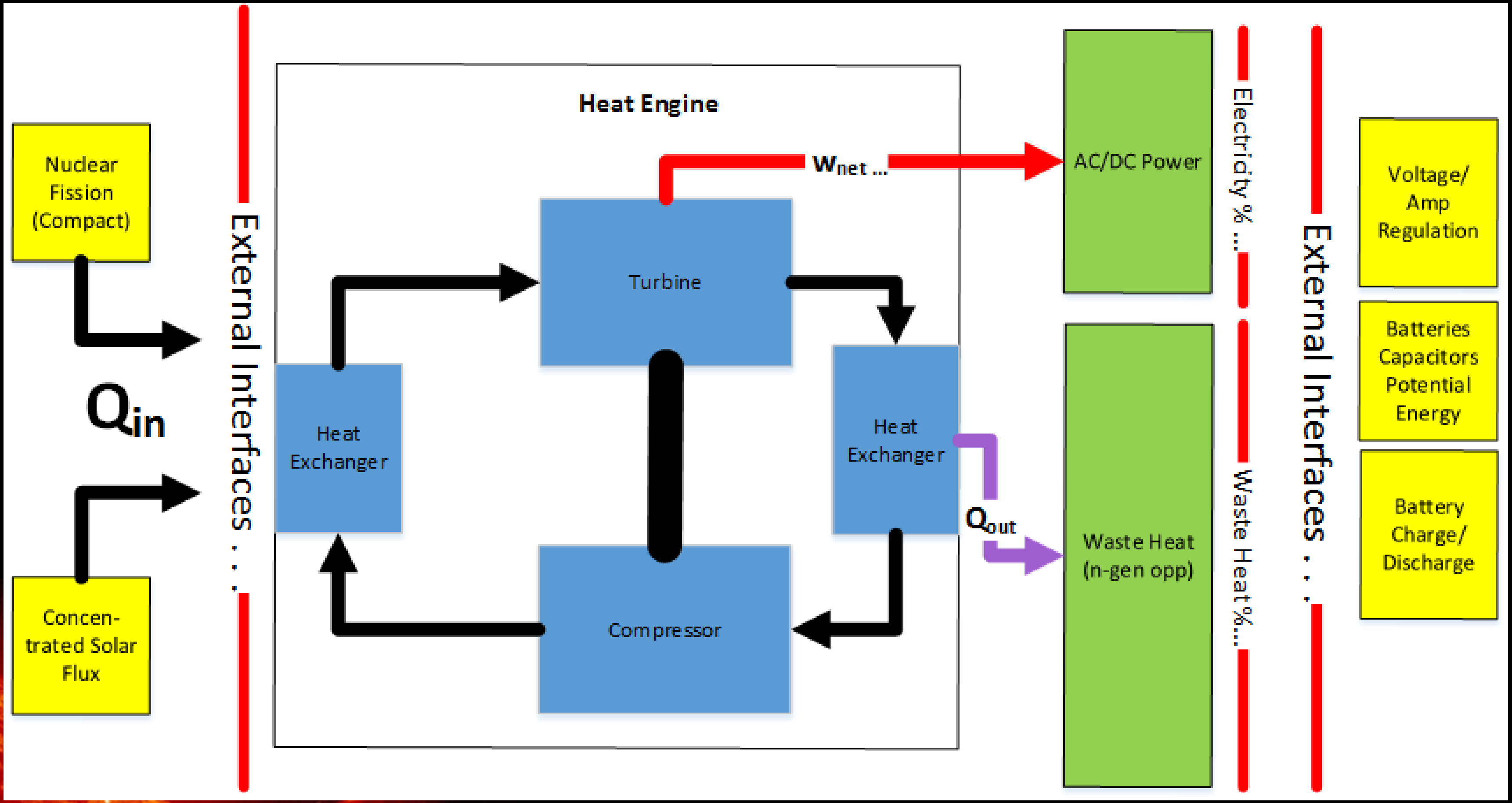
Power/Heat Management

- Instrumentation (e.g., Sensors, Gauges, and Actuators)
- Data Handling, Storage, and Processing
- State Model
- Control Logic
- Management Operations Control Applications (MOCA)

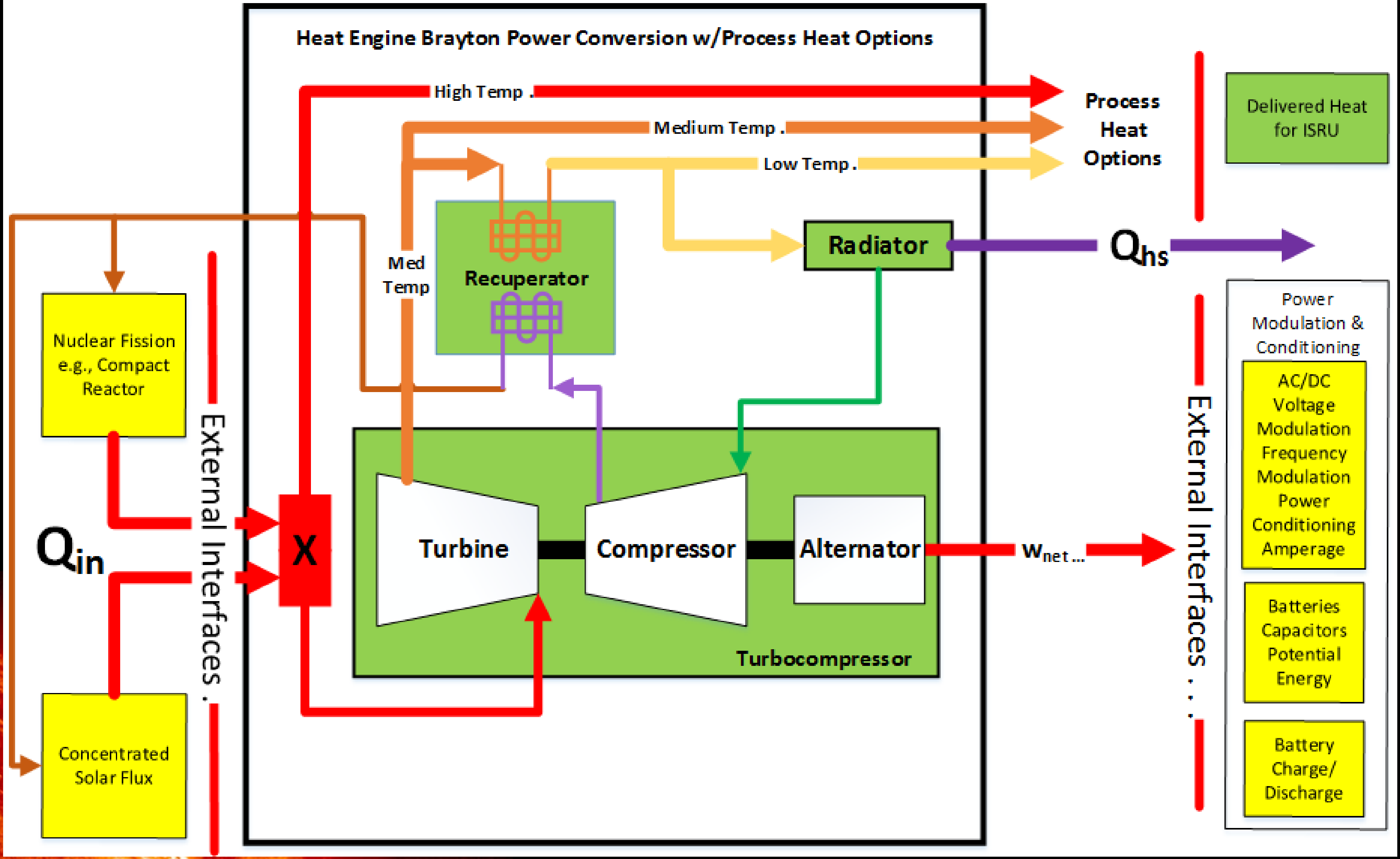
External Interfaces . . .

Delivered Power For Loads

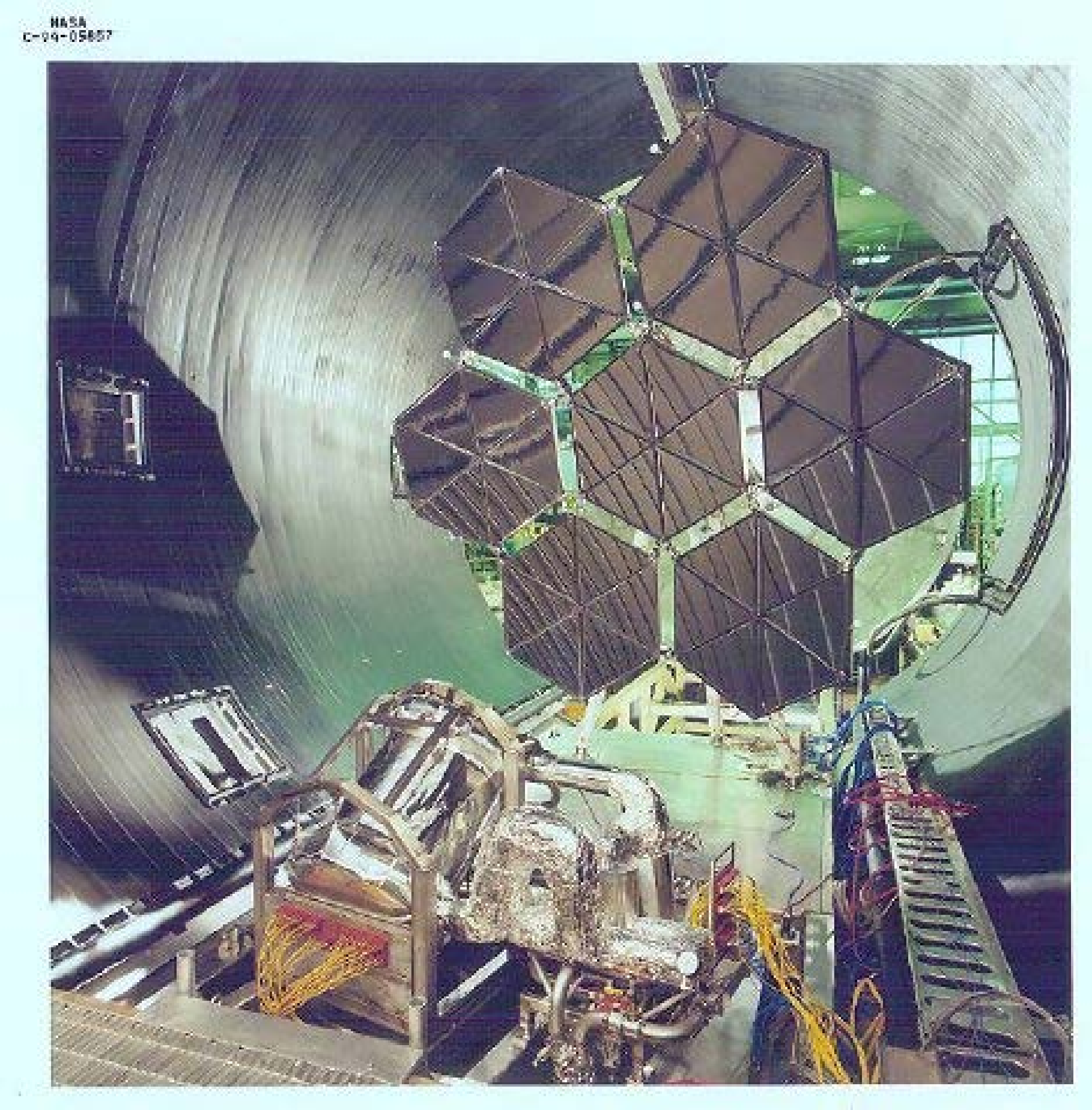
Brayton Cycle Heat Engine Block Diagram (Simple)



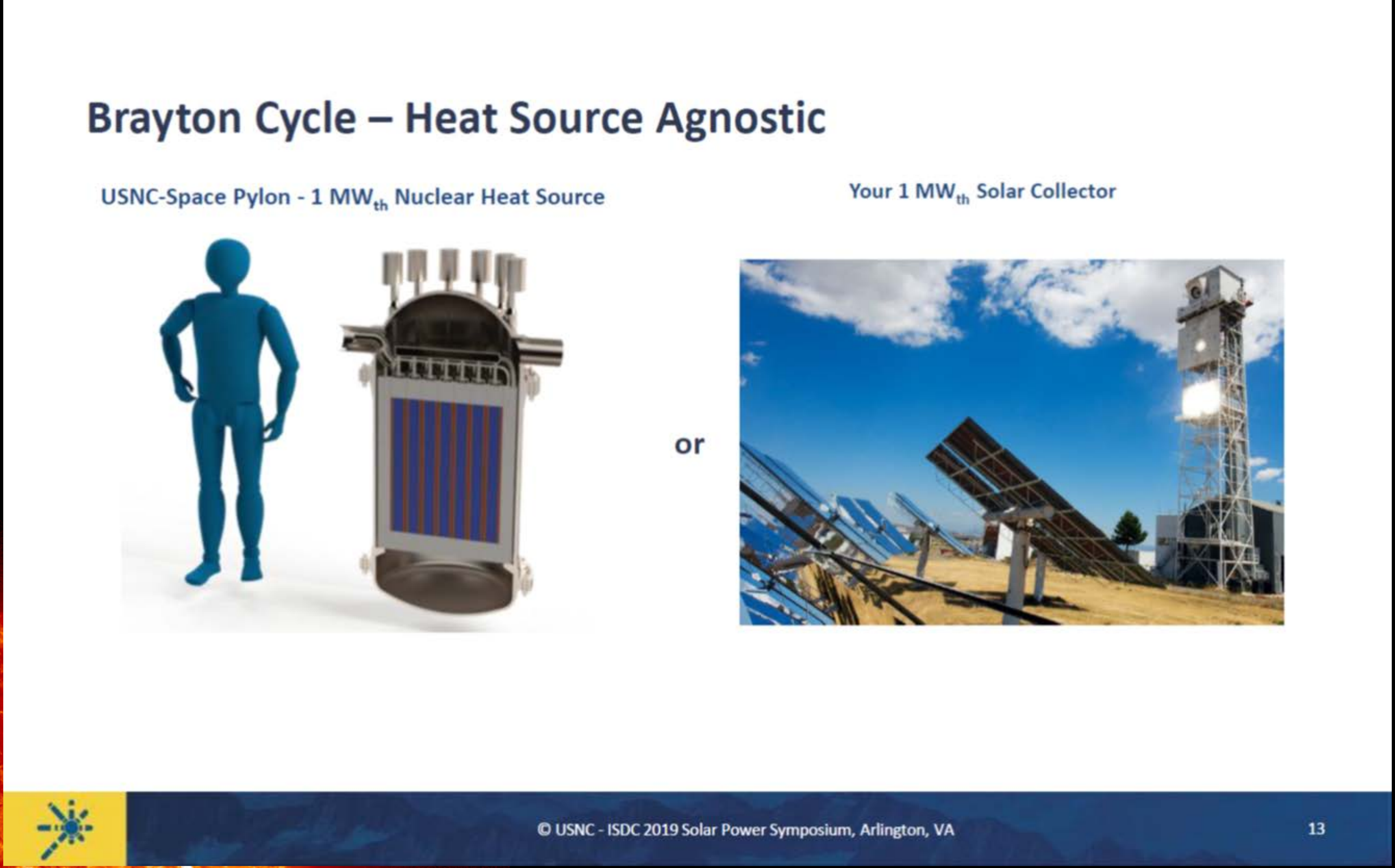
Brayton Cycle Hear Engine Block Diagram w/Process Heat Options



2kW Solar Dynamic Ground Test Demonstration at NASA LeRC/GRC



Compact Nuclear & Solar Dynamic Interoperable Brayton Conversion



Brayton Cycle – Heat Source Agnostic

USNC-Space Pylon - 1 MW_{th} Nuclear Heat Source

or

Your 1 MW_{th} Solar Collector

© USNC - ISDC 2019 Solar Power Symposium, Arlington, VA

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Trade Space: Data Sets

- **First data set:** Vendor User’s Guides for the NASA Commercial Lunar Payload Services (CLPS) contract lunar lander spacecraft (fourteen contractors are now qualified to participate)

  -- Astrobotic Technology
  -- Ceres Robotics
  -- Draper
  -- Intuitive Machines
  -- Masten Space Systems
  -- Orbit Beyond
  -- SpaceX
  -- Blue Origin
  -- Deep Space Systems
  -- Firefly Aerospace
  -- Lockheed Martin Space
  -- Moon Express
  -- Sierra Nevada Corporation
  -- Tyvak Nano-Satellite Systems

- **Second data set:** Customer power requirements for deployable payloads in increments of 1 kW, 10 kW, 100 kW, and 1000 kW

- **Third data set:** Theoretical and experimental test data on transmitter options, rectenna/receiver options, and the end-to-end efficiency for microwave, millimeter wave, and infrared/optical frequencies.

Trade Space: Methodology

- Working from the potential available input power increments, a *similar/comparable scaling* can be deduced.
- The DC-to-Beam conversion efficiency can be factored in, yielding estimates for the *maximum power output electrical and the maximum power output thermal*.
- Using the collection efficiency method, the *received power* can be calculated for various distances of interest using existing theoretical and experimental data tabulated into the proposed framework.
- *As the TBDs in the framework are resolved the resulting values can be translated into power and ancillary services infrastructure package preliminary designs that are both robotic and EVA compatible for peer review*.

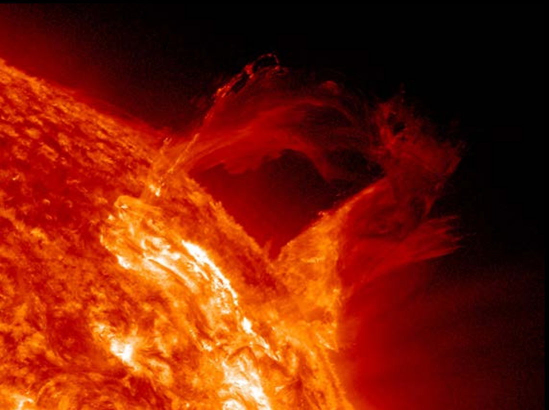
Definition of Accommodation Requirements

- As part of the NASA CLPS contract vendors are required to prepare *Payload Users Guides (PUGs)* which *document the proposed lander interfaces, payload accommodations requirements* including customer utilities, and operational rules. The availability of the detailed versions and release of the content of these PUGs is currently constrained by Non-Disclosure Agreements.
- The *development of Cislunar Utility Technologies* (e.g., power and ancillary services including but not limited to communications, data relay, navigation, and time), *Integration & Interface Standards by public-private partnerships can and will lower NASA's infrastructure and utility costs for evolving Cislunar operations*.
- This work will give the participating Cislunar partners *incentive to design, build, and demonstrate new and innovative scalable infrastructure elements* that provide required utility services in a timely manner for inclusion in the CLPS flights and infrastructure follow-on development.

Definition of Accommodation Requirements

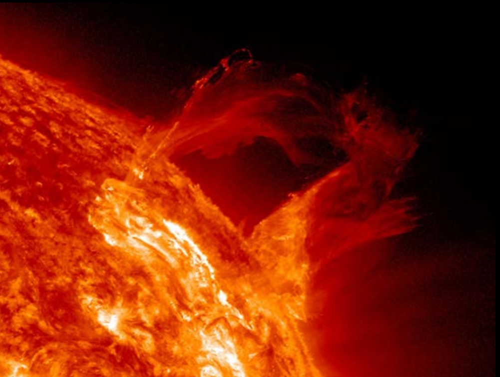
- More specifically, a critical subset of interface standards for:
  - power,
  - data,
  - voice and video communications,
  - navigation,
  - time,
  - thermal management,
  - water,
  - atmospherics,
  - waste management, and
  - control
- These standards need to be defined in terms of:
  - their functional accommodation requirements;
  - satisfactory and sufficient design elements; and
  - prototyped, tested, and specific interface standards codified as appropriate

➔ Cislunar Utility Technologies, Integration & Interface Standards.



Definition of Accommodation Requirements

- What is the Maximum Input Power Available?
- What is the DC to Beam Conversion Efficiency?
- What is the Maximum Power Output Electrical & Thermal?
- What are the Transmitter & Mass Budget?
- What is the Receiver Thermal Absorption Requirement
- What is the Receiver Beam Reflection %?
- What is the Customer Received Power @1 m,10 m,100 m,1 km,10 km,100 km?
- When is the power available?
- What is the power quality specification?
- What are the accommodation requirements?
  - -- Physical attachment interface
  - -- Data connection interface
  - -- Launch environment
  - -- Operating environment
  - -- Power connection interface
  - --Thermal management interface
  - -- Landing environment
  - -- Quiescent/keep-alive environment
- What are the safety, quality assurance, and quality control considerations?



Theoretical & Experimental Efficiency

Calculations:		
Input Power	$P_{Input} = 0 \text{ to } 1000$	Watts
Wavelength	$\lambda = C / f$	cm
Diameter of the Transmitter Aperture	D	cm
Transmitter DC-to-MW Efficiency %	$\eta_{\text{DC-to-MW}}$	dimensionless
- Transmitter Beam Forming Efficiency %	$\eta_{\text{Beam Forming}}$	dimensionless
Total Radiated Power from Transmitter	$P_{Tx} = (P_{Input})*(\eta_{\text{DC-to-MW}})*(\eta_{\text{Beam Forming}})$	Watts
Range	R	cm
Free Space Transmission Efficiency %	$\eta_{\text{Free Space Trans}}$	dimensionless
Diameter of the Receiver Aperture	W	cm
Zeta where $0 < \zeta < 3$ Zeta relates the physical parameters of the power beaming system to the collection efficiency of the power transfer	$\zeta = \frac{D\,W}{\lambda\,R}$	dimensionless
Diameter of the Transmitter	D	cm
Diameter of the Receiver	W	cm
Wavelength	λ	cm
Range	R	cm
Collection Efficiency @SLR of 25 dB		
Power Received at Rectenna	$P_{Received} =$ (Collection Efficiency) * (P_{Tx})	Watts
Receiver MW-to-DC Conversion Efficiency %	$\eta_{\text{MW-to-DC}}$	dimensionless
- Receiver Beam Reflectivity Loss	Component of $\eta_{\text{MW-to-DC}}$	
- Receiver Thermal Absorption Requirement	Component of $\eta_{\text{MV-to-DC}}$	
Power Delivered to Customer	$P_{delivered} = (P_{Received})*(\eta_{\text{MW-to-DC}})$	Watts

Microwave Theoretical & Experimental Efficiency

Published Year	Input Power (W)	DC to MW Conversion Efficiency	Beam Forming Antenna Efficiency	Free Space Transmission Efficiency	MV to DC Conversion Efficiency	Output Power (W)	DC -to-DC Projected Efficiency	DC -to-DC Demonstrated Efficiency	DC -to-DC Theoretical Efficiency		
1992	100	90%	90%	90%	90%	66	66%	54%	76%	< 6 GHz	(1) Raytheon
2016	100	95%	90%	90%	95%	73	73%	Extrapolated	95%	< 6 GHz	(2) XISP-Inc
2016	100	60%	80%	90%	72%	31	31%	Extrapolated	95%	Higher Frequencies	(2) XISP-Inc
2016	100	60%	80%	90%	72%	31	31%	Extrapolated	95%	Higher Frequencies	(2) XISP-Inc
2019	6000	100%	100%	100%	18%	1064	18%	Collection Efficiency Calculation	TBD	26.5 GHz @200 m, 1 m^2 Tx & Rx areas	(3) XISP-Inc
2019	6000	100%	100%	100%	30%	1809	30%	Collection Efficiency Calculation	TBD	36 GHz @200 m, 1 m^2 Tx & Rx areas	(3) XISP-Inc
2019	6000	100%	100%	100%	83%	4964	83%	Collection Efficiency Calculation	TBD	95 GHz @200 m, 1 m^2 Tx & Rx areas	(3) XISP-Inc
2020	100	78%	85%	90%	84%	50	50%	Service Baseline	95%	Frequency Agnostic (but not Atheist)	XISP-Inc, aspirational

NOTES:

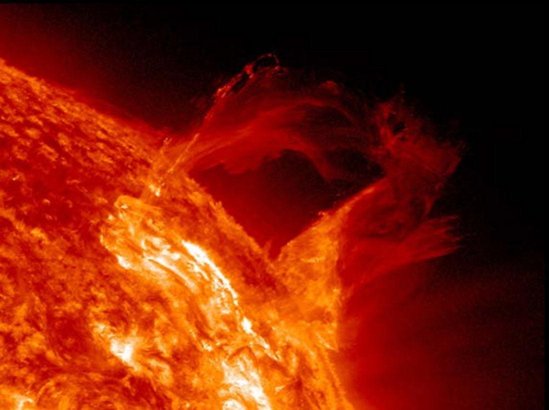
1	William C. Brown, Life Fellow, IEEE, and E. Eugene Eves, Beamed Microwave Power Transmission and its Application to Space, IEEE Transactions On Microwave Theory and Techniques, Vol. Ro, No. 6. June 1992
2	Gary P. Barnhard, Daniel Faber, Space-to-Space Power Beaming - An Evolving Commercial Mission to Unbundle Space Power Systems to Foster Space Applications International Astronautical Congress, Guadalajara. Mexico 2016
3	Gary P. Barnhard, Dr. Seth D. Potter, Challenges of Space Power and Ancillary Services Beaming: Key to Opening the Cislunar Marketplace, International Astronautical Congress Washington, DC 2019

Similar tables are included for other frequencies

Blazing the Path Forward

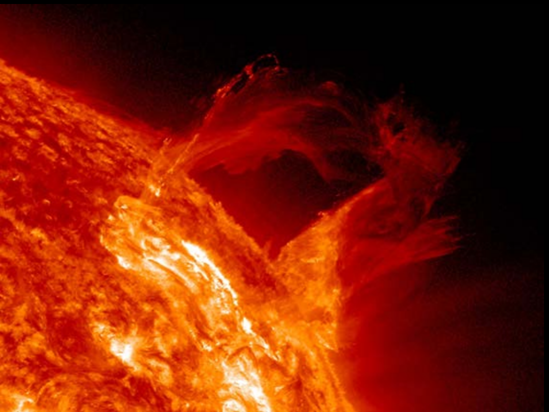
The path forward for this work requires:

- *finishing the characterization* of the power and ancillary services beaming payload packages with all of the NASA CLPS contract vendors,
- *orchestrating the vendor round robin for interface testing* (e.g., the XISP-Inc ACO proposal on Cislunar Utility Technologies, Integration & Interface Standards proposed with NASA ARC),
- *leveraging the earliest possible flight opportunities* with other missions for data (e.g., the XISP-Inc ACO proposal on Interoperable Network Communication Architecture-Applications (INCA-A) with NASA GSFC on the Laser Communications Relay Demonstration mission, and the XISP-Inc ISS National Lab Space-to-Space Power and Ancillary Services Beaming TD^3 mission.



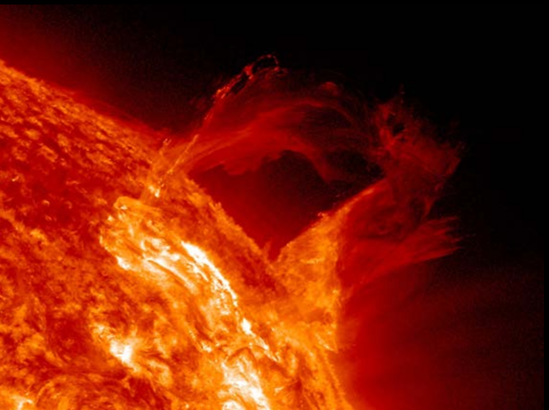
Conclusions (1 of 2)

- *We need to populate performance tables in a systematic way*, all be it initially with data which was not designed for that purpose.
- *We need to systematize the approach to theoretical and experimental work* in this area (i.e., it is an applied engineering problem).
- *We have to justify what is a "scalable Increment"* balancing achievability with meaningful performance within a reasonable time frame.
- Heuristic: *If a potential power system increment can not provide more power than it takes to field it then it is not a worth building*.
- It is important that *system design should be frequency agnostic but not atheistic* when it comes to specific applications.
- The *combination of technologies needed to achieve a system level TRL must address the component level TRLs*.
- We must *systematize the approach to integrating technologies* into feasible systems.
- At present we do not have the data to fill out the entire performance table but it provides a *framework for considering the trade space in a systematic manner*.



Conclusions (2 of 2)

- We need to understand the *potential payoff of developing different sectors of the solution space*.
- We need to find the *areas of the solution space which yield financial returns of sufficient magnitude to warrant government and private investment.*
- This approach allows us to:
  - *Identify opportunities for synergy*
  - *Systematize the resolution of TBDs*
  - *Determine where to allocate resources*



Surface-to-Surface Power Beaming Backup Slides

- Applications
  - Near Term CLPS Support
  - ISRU Prospecting
  - Infrastructure
- Accommodation Requirement Considerations
- Efficiency Tables

WaterWitch Lunar Regolith Processing

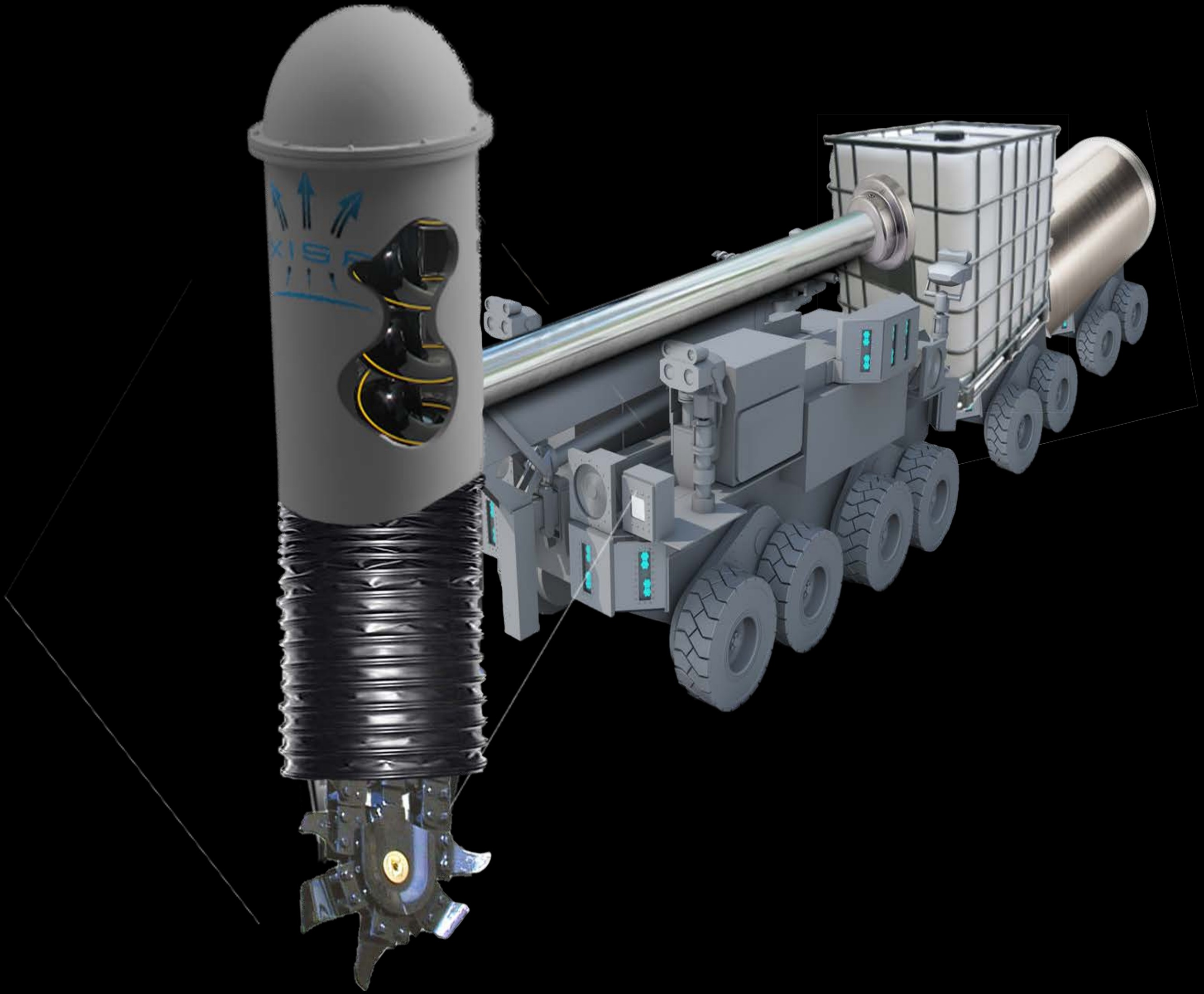
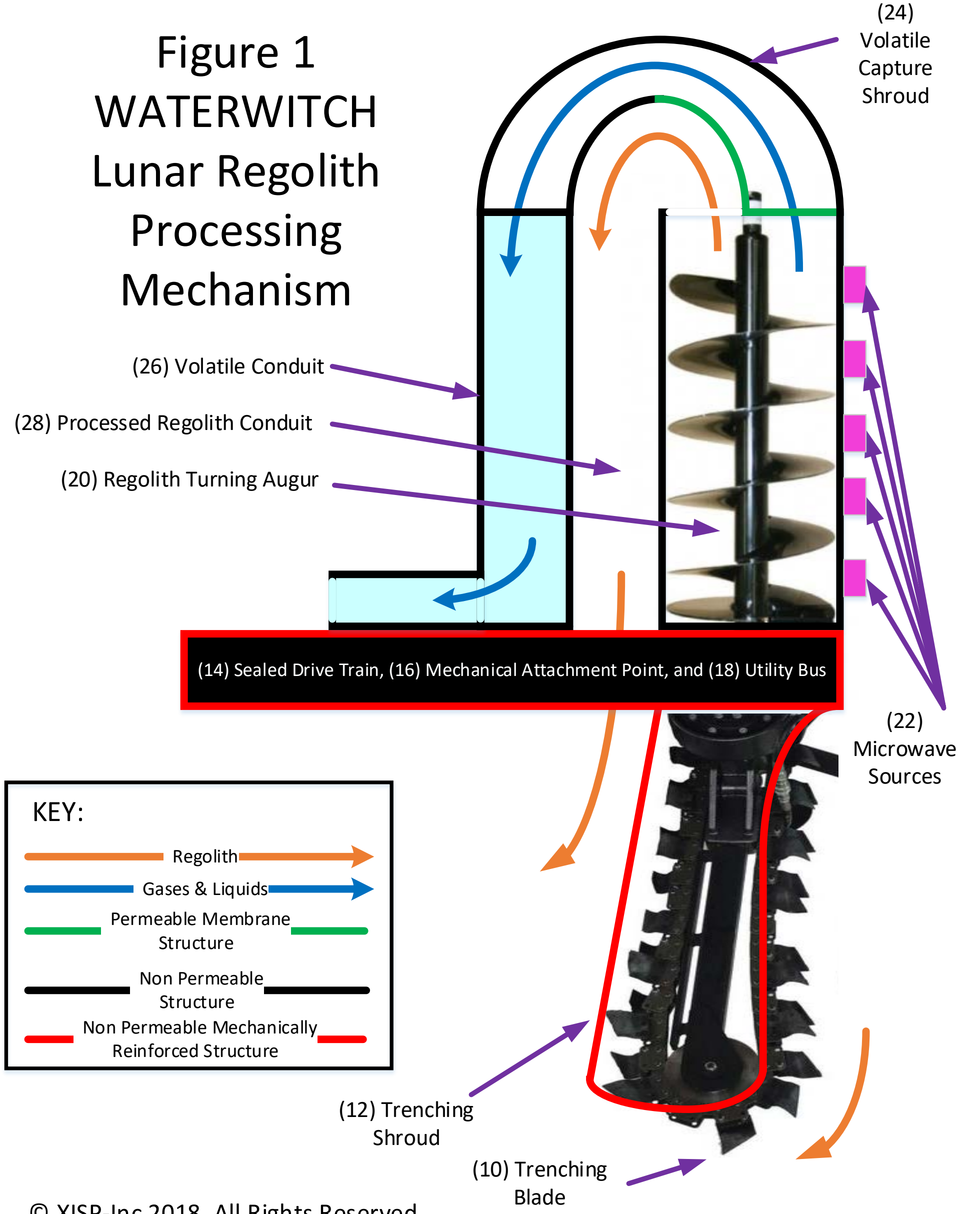


Figure 1
WATERWITCH Lunar Regolith Processing Mechanism



Evolved Surface-to-Surface Beaming

Cislunar Marketplace Initiative

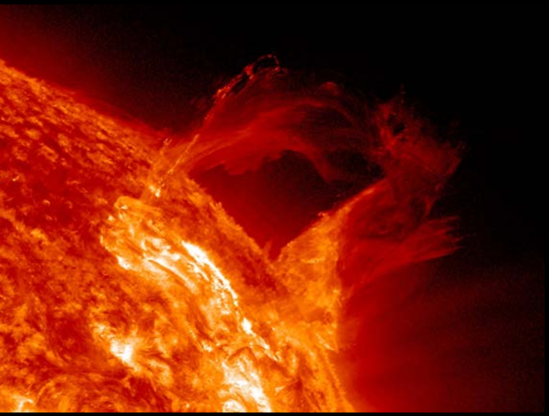
IAC 2019
Washington, DC
Oct 21-25, 2019

cislunar.nss.org

What’s Next?

Lunar Power & Light Company

an XISP-Inc Consortium



Don’t wait for the future, help us build it!

www.xisp-inc.com

Resources

Commercial Lunar Propellant Architecture: A Collaborative Study of Lunar Propellant Production
http://cislunar.nss.org/wordpress/wp-content/uploads/2018/11/Commercial-Lunar-Propellant-Architecture.pdf

XISP-Inc Projects:
http://www.xisp-inc.com/index-6-projects.html

Space Development Foundation:
http://www.spacedevelopmentfoundation.org

Cislunar Marketplace:
https://cislunar.nss.org

Definition of Accommodation Requirements

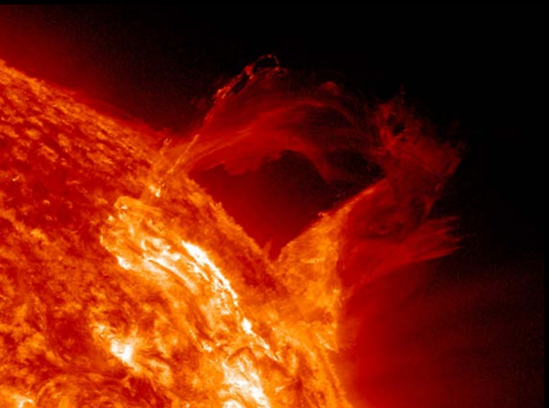
- **What is the Maximum Input Power Available?**
  - Based the preliminary designs of the CLPS landers and a projected worst case of interest
  - end-to-end efficiency value of 10% for power beaming applications the lower bound of Maximum Power
  - Input is posited to be .1 kW. The range of values are then extended by the next four orders of
  - magnitude (1, 10, 100, and 1000 kW). This bridges the solution space from initial payloads to facility scale modular building blocks.
- **What is the DC to Beam Conversion Efficiency?**
  - Based on a combination of theory, test, and fielded systems, so far as power beaming is concerned the DC-to-Beam Conversion Efficiency (i.e., the combination of DC-to-MW/Infrared/Optical Conversion Efficiency which ranges from 20% to 95% and the Beam Forming Antenna Efficiency ranges from 80% to 99%). The aspirational goal is to meet or exceed 78% across the viable solution space.

Definition of Accommodation Requirements

- **What is the Maximum Power Output Electrical?**
  - This is a calculated value based on the actual input power and the projected DC-to- Beam Conversion Efficiency.
- **What is the Maximum Power Output Thermal?**
  - This is a calculated value based on the actual input power, the projected DC-to-Beam Conversion Efficiency, and the law of conservation of energy. This thermal output must be accommodated by some combination of spacecraft thermal absorption and black body radiation to space.
- What is the Transmitter Mass Budget?
  - Extrapolating from currently available components the projected minimum mass for a receiver (rectenna)/transceiver is at least 10 kg for Power Input up to .1 kW. Based on prior work minimum mass for transmitter/transceiver is at least 15 kg for Power Input up to 1 kW. The range of values are then extended by the next four orders of magnitude (100, 1000, and 10000 kg). This bridges the solution space from initial payloads to facility scale modular building blocks.

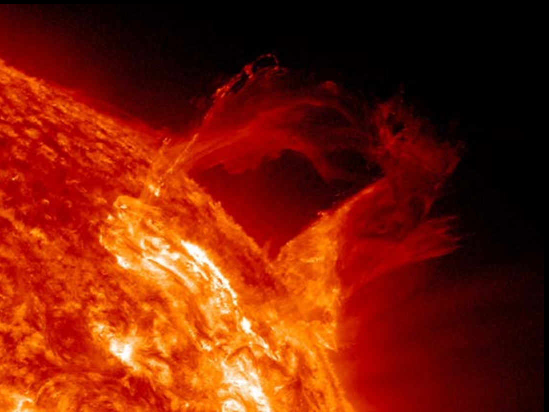
Definition of Accommodation Requirements

- **What is the Receiver Mass Budget?**
  - Based the currently available components the projected minimum mass for transmitter/transceiver is at least .1 kg for Power Input up to .1 kW. Based on prior work minimum mass for transmitter/transceiver is at least 15 kg for Power Input up to 1 kW. The range of values are then extended by the next four orders of magnitude (100, 1000, and 10000 kg). This bridges the solution space from initial payloads to facility scale modular building blocks.
- **What is the Receiver Thermal Absorption Requirement?**
  - This is a calculated value based on the actual input power, the projected Beam-to-DC Conversion Efficiency and the law of conservation of energy. This thermal output must be accommodated by some combination of spacecraft thermal absorption, the receiver beam reflection, and black body radiation to space.



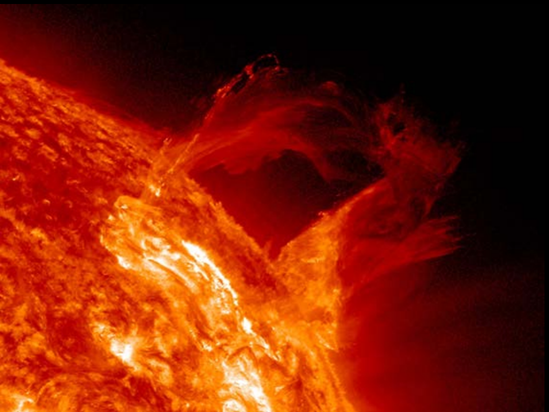
Definition of Accommodation Requirements

- **What is the Receiver Beam Reflection %?**
  - This is a calculated value based on a combination of the angle of incidence and the spectral characteristics of the rectenna.
- **What is the Customer Received Power @ increments of interest?**
  - This is a calculated value of customer received power is based on the diameter of the transmitter (i.e., .1 m^2, 0.5 m^2, or 1 m^2), the diameter of the rectenna (i.e., .1 m^2, 0.5 m^2, or 1 m^2), the wavelength of the beam (i.e., based on frequency conversion from 2.45 GHz, 5.8 GHz, 26.5 GHz, 36 GHz, 92 GHz, and 95 GHz), the range between the transmitter and the rectenna, as well as the projected Collection Efficiency (correlated from zeta).



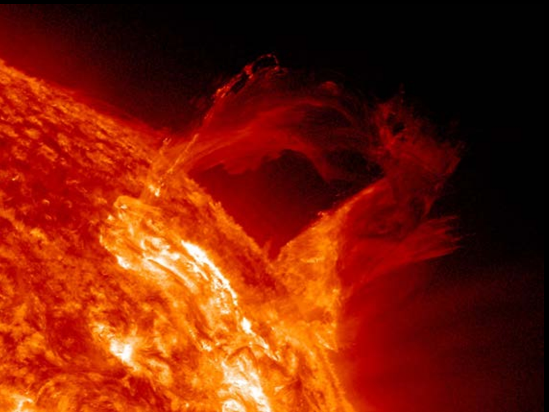
Definition of Accommodation Requirements

- **When is the power available?**
  - This is a calculated value based on the CLPS landers nominal mission timeline, as well as total available power.
- **What is the power quality specification?**
- The assumption is that input power voltage will not vary by more than 3% and will effectively be a pure sine wave.



Definition of Accommodation Requirements

- **What are the accommodation requirements?**
  - Physical attachment interface
  - Power connection interface
  - Data connection interface
  - Thermal management interface (if applicable)
  - Launch environment
  - Landing environment
  - Operating environment
  - Quiescent/keep-alive environment
- **What are the safety, quality assurance, and quality control considerations?**
  - Two fault tolerant beam inhibit with fail safe



Infrared & Optical Theoretical & Experimental Efficiency

Published Year	Input Power (W)	DC to Infrared Conversion Efficiency	Beam Forming Antenna Efficiency	Free Space Transmission Efficiency	Infrared to DC Conversion Efficiency	Output Power (W)	DC -to-DC Projected Efficiency	DC -to-DC Demonstrated Efficiency	DC -to-DC Theoretical Efficiency		
2019	100	90%	99%	99%	40%	35	35%	32%	TBD		(1),(2) JX Crystals

NOTES:

1 Lewis Fraas, Solar Power from Space, ThermoPhotoVoltaic (TPV) Cells & IR Power Beaming ISDC June 5, 2019

2 L. M. Fraas & R.C. Knechtli, Monolithic Triple Junction InGaP/GaInAs/Ge CPV Cell, IEEE Photovoltaic Specialist Conference, 1978

Published Year	Input Power (W)	DC to Optical Conversion Efficiency	Beam Forming Antenna Efficiency	Free Space Transmission Efficiency	Optical to DC Conversion Efficiency	Output Power (W)	DC -to-DC Projected Efficiency	DC -to-DC Demonstrated Efficiency	DC -to-DC Theoretical Efficiency		
2019	100	90%	99%	99%	49%	43	43%	43%	TBD	Extrapolated Piecewise Values	(1) XISP-Inc
2019	100	85%	99%	99%	50%	42	42%	43%	TBD		(2),(3) PowerLight Technologies

NOTES:

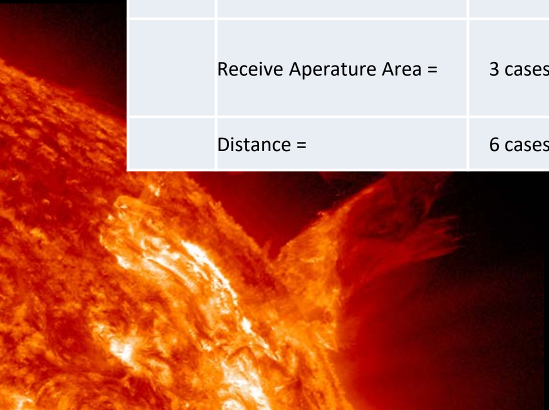
1 Gary P. Barnhard, Dr. Seth D. Potter, Challenges of Space Power and Ancillary Services Beaming: Key to Opening the Cislunar Marketplace, International Astronautical Congress Washington, DC 2019

2 Paul Crump, et al.,SHEDs Funding Enables Power Conversion Efficiency up to 85% at High Powers from 975-nm Broad Area Diode Lasers. Retrieved October 3, 2019.

3 Tobias P. Koenning, Dr. H. G. Treusch , Power Beaming with Diode Lasers, 2008.

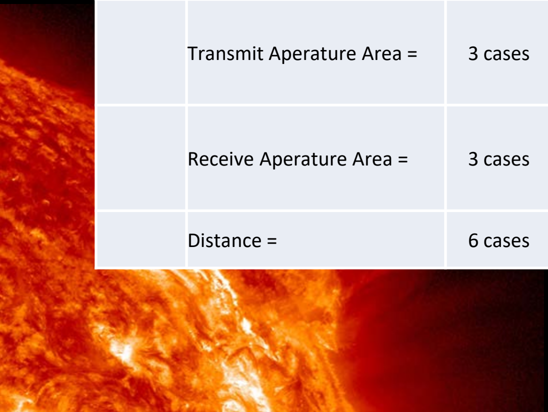
Microwave/Millimeter Wave Power Distribution
(2 GHz to 300 GHz / 15 cm to 1 mm)

Max Power Input (kW)	DC to Beam Conversion Efficiency (%)	Max Power Output Electrical (kW)	Max Power Output Thermal (kW)	Transmitter Mass Budget (kg)	Receiver Mass Budget (kg)	Receiver Thermal Absorption (W)	Receiver Beam Reflection (%)	Customer Received Power @ 1m (W)	Customer Received Power @ 10m (W)	Customer Received Power @ 100 m (W)	Customer Received Power @ 1 km (W)	Customer Received Power @ 10 km (W)	Customer Received Power @ 100 km (W)
0.1	TBD	TBD	TBD	10	0.1	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
1	TBD	TBD	TBD	15	0.1	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
10	TBD	TBD	TBD	100	1	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
100	TBD	TBD	TBD	1000	10	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
1000	TBD	TBD	TBD	10000	100	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Notes:	Frequency =		6 cases	2.45 GHz, 5.8 GHz, 26.5 GHz, 36 GHz, 92 GHz, and 95 GHz					Example: Raytheon Active Denial System, 3rd Generation				
	Transmit Aperature Area =		3 cases	0.1	m^2	0.5	m^2	1	m^2				
	Receive Aperature Area =		3 cases	0.1	m^2	0.5	m^2	1	m^2				
	Distance =		6 cases	1 m, 10 m, 100 m, 1 km, 10 km, 100 km									



Infrared (Far, Middle, and Near) Band (300 GHz to 430 THz / 1 mm to 700 nm) Power Distribution

Max Power Input (kW)	DC to Beam Conversion Efficiency (%)	Max Power Output Electrical (kW)	Max Power Output Thermal (kW)	Transmitter Mass Budget (kg)	Receiver Mass Budget (kg)	Receiver Thermal Absorption (W)	Receiver Beam Reflection (%)	Customer Received Power @ 1m (W)	Customer Received Power @ 10m (W)	Customer Received Power @ 100 m (W)	Customer Received Power @ 1 km (W)	Customer Received Power @ 10 km (W)	Customer Received Power @ 100 km (W)
0.1	TBD	TBD	TBD	10	0.1	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
1	TBD	TBD	TBD	10	0.1	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
10	TBD	TBD	TBD	100	1	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
100	TBD	TBD	TBD	1000	10	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
1000	TBD	TBD	TBD	10000	100	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Notes:	Frequency =		1 Case	1.5	Micron		Example:	JX Crystals	1500 Nanometers				
	Transmit Aperature Area =		3 cases	0.1	m^2	0.5	m^2	1	m^2				
	Receive Aperature Area =		3 cases	0.1	m^2	0.5	m^2	1	m^2				
	Distance =		6 cases	1 m, 10 m, 100 m, 1 km, 10 km, 100 km									



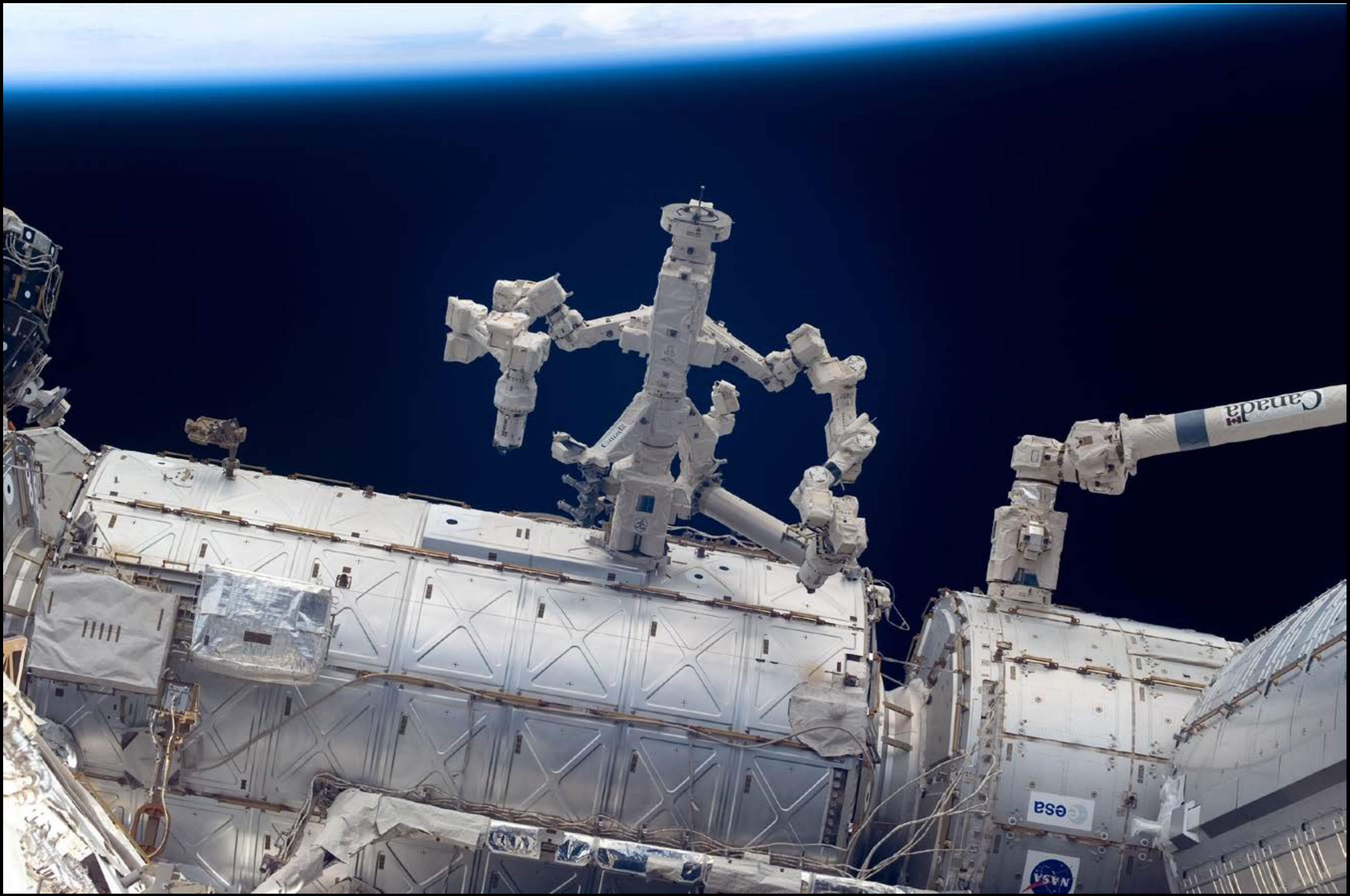
Near Infrared (215 THz to 400 THz / 760 to 2500 nm) to Visible Light (428 THz to 750 THz / 700 to 400 nm) Optical Power Distribution

	DC to Beam	Max Power	Max Power	Transmitter	Receiver	Receiver	Receiver	Customer	Customer	Customer	Customer	Customer	Customer
Max Power	Conversion	Output	Output	Mass	Mass	Thermal	Beam	Received	Received	Received	Received	Received	Received
Input	Efficiency	Electrical	Thermal	Budget	Budget	Absorption	Reflection	Power @ 1m	Power @ 10m	Power @ 100 m	Power @ 1 km	Power @ 10 km	Power @ 100 km
(kW)	(%)	(kW)	(kW)	(kg)	(kg)	(W)	(%)	(W)	(W)	(W)	(W)	(W)	(W)
0.1	TBD	TBD	TBD	10	0.1	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
1	TBD	TBD	TBD	10	0.1	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
10	TBD	TBD	TBD	100	1	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
100	TBD	TBD	TBD	1000	10	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
1000	TBD	TBD	TBD	10000	100	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Notes:	Frequency =		1 Case	1.5	Micron		Example:	JX Crystals	1500 Nanometers				
	Transmit Aperature Area =		3 cases	0.1	m^2	0.5	m^2	1	m^2				
	Receive Aperature Area =		3 cases	0.1	m^2	0.5	m^2	1	m^2				
	Distance =		6 cases	1 m, 10 m, 100 m, 1 km, 10 km, 100 km									

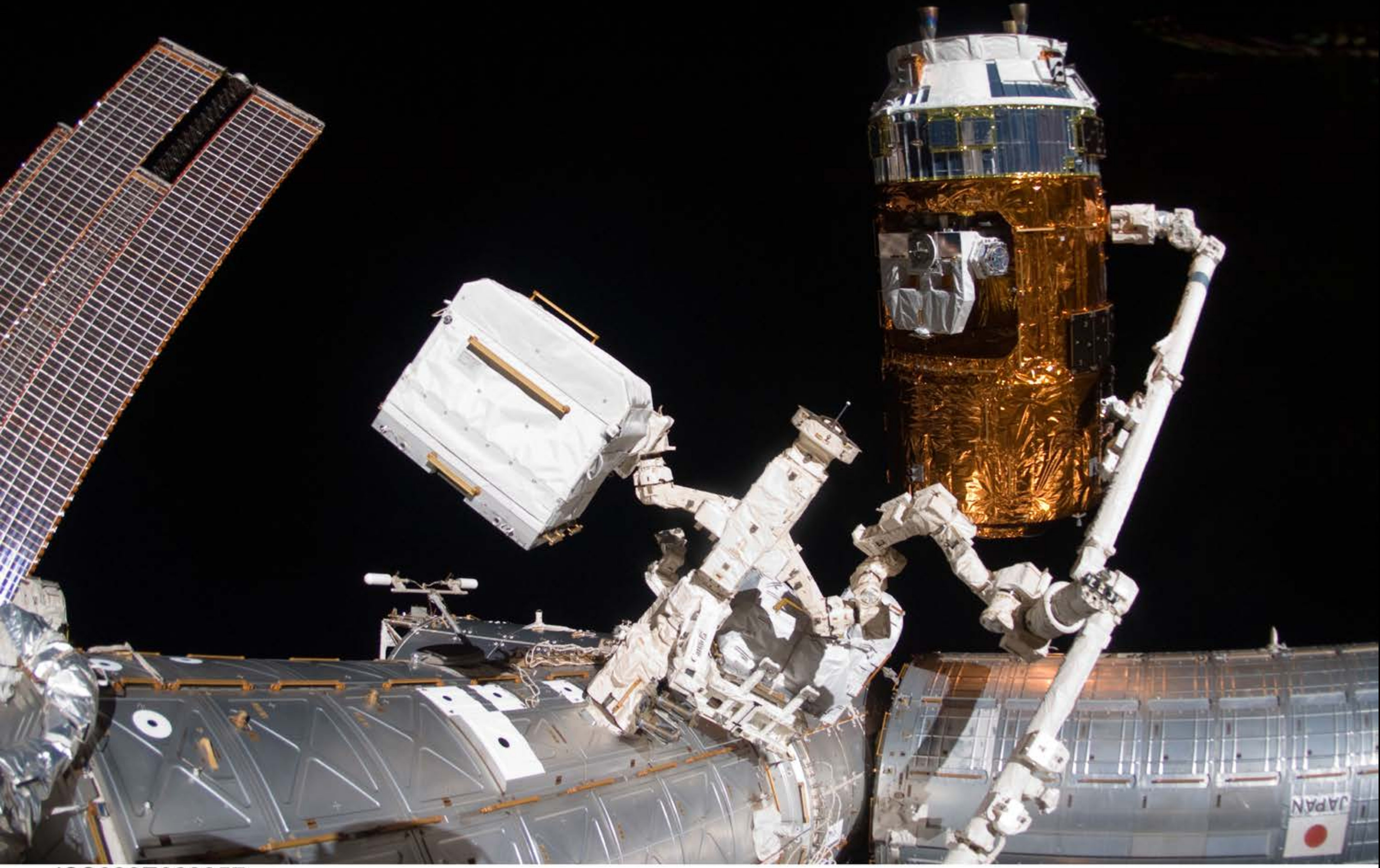
Example 2: Management Operations Control Applications (MOCA)

- **PROBLEM:** Living and working in space environments requires a partnership between humans, robotic, and automated systems.
- **HYPOTHESIS:** A mutable locus of shared control is required between:
  - Remotely Supervised, Teleoperated, Physically Present, and Autonomous Operations
  - Ground and Inflight Operations
  - Scheduled and Dynamic Operations
  - Defined and Sensed Environments
  - Referenced, Predicted, and Sensed Geometry
- **OUTCOME:** Orchestrating symbiosis addresses established problems and provides a framework for addressing emergent ones that biases operational outcomes towards success by enabling a mutable locus of shared control.

Extra Vehicular Robotics . . .



EVR Tasking . . .



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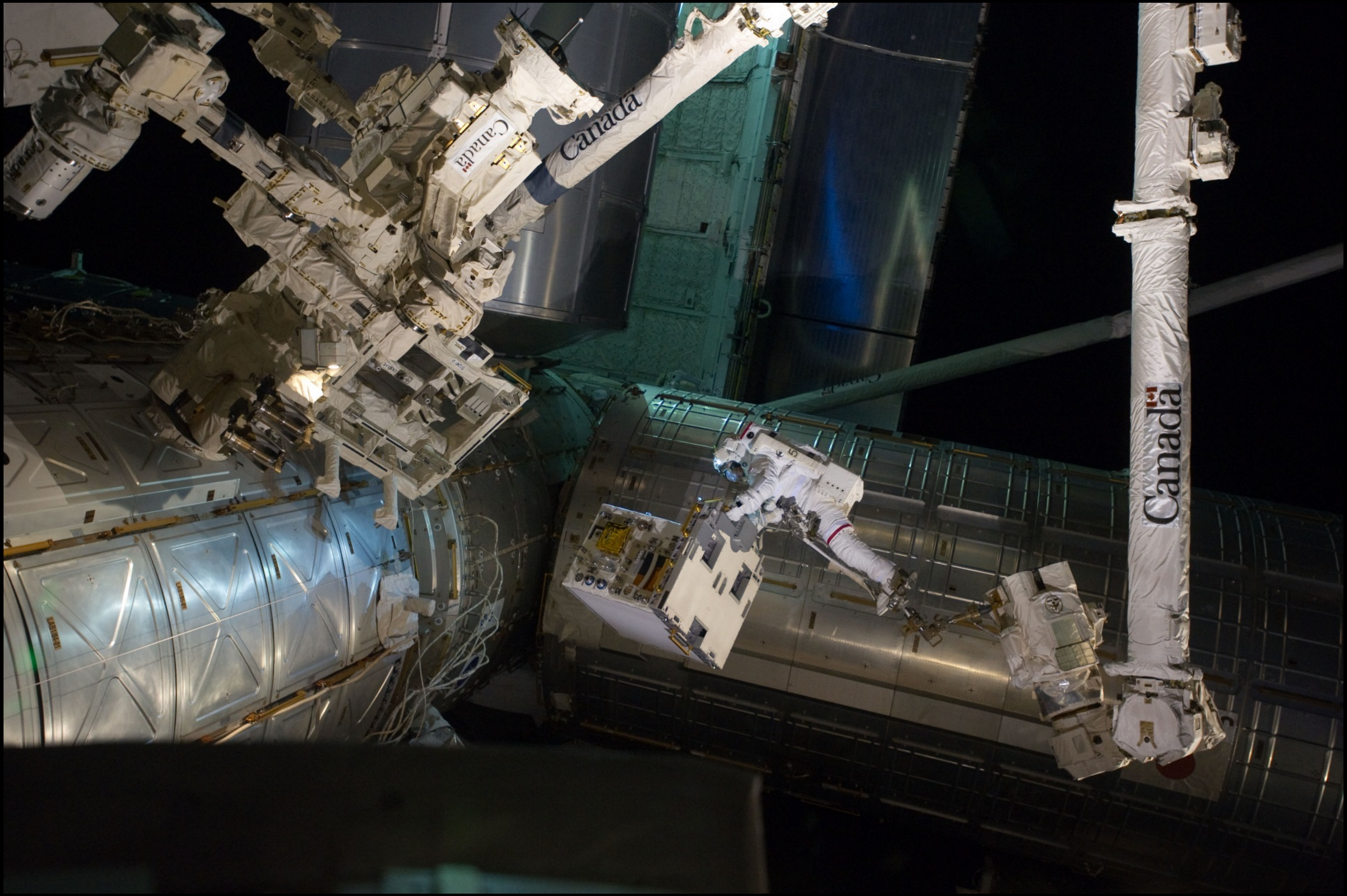
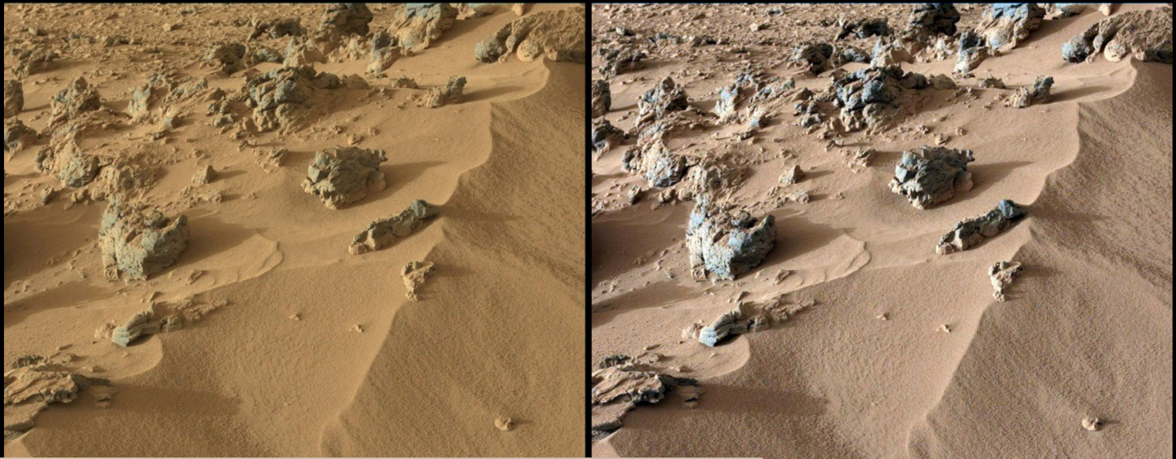
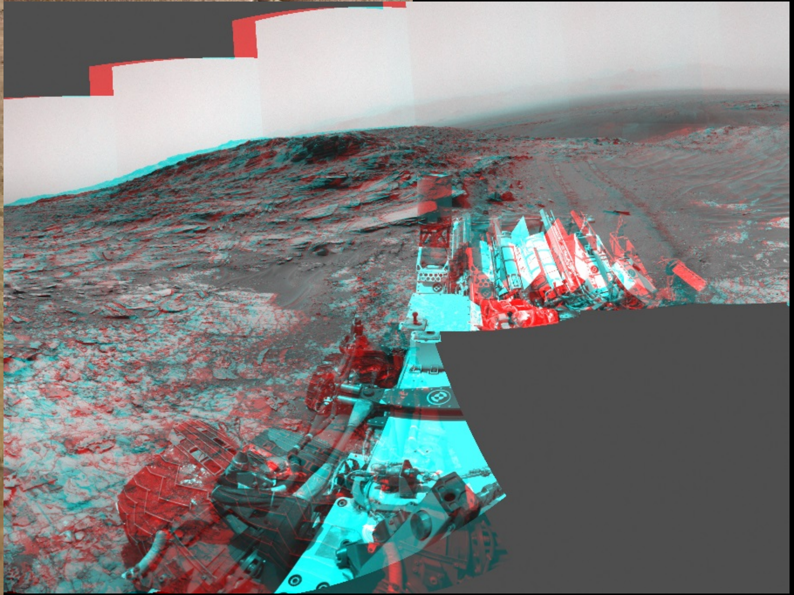
Robotics & EVA Crew . . .



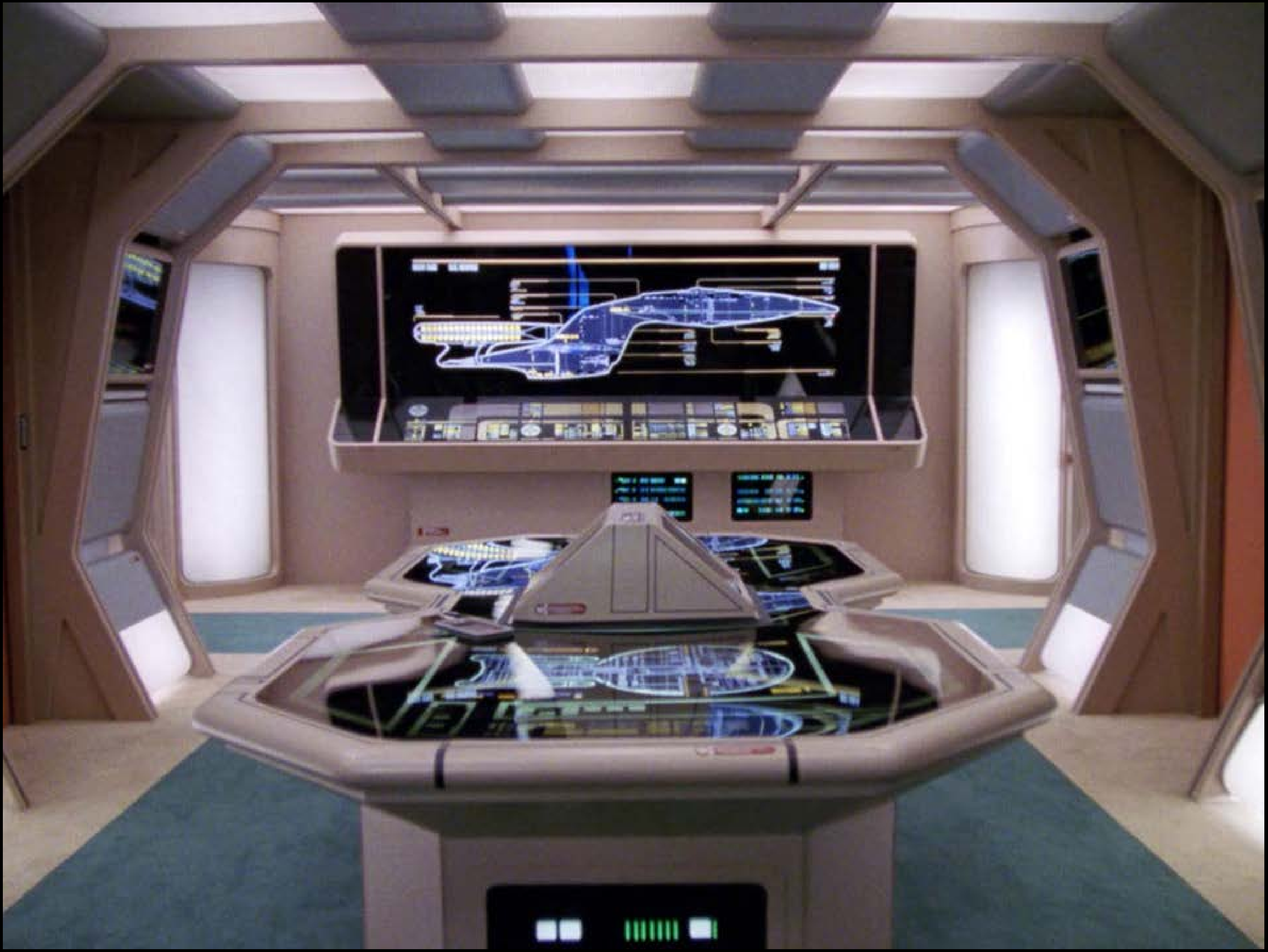
So you want to roam . . .



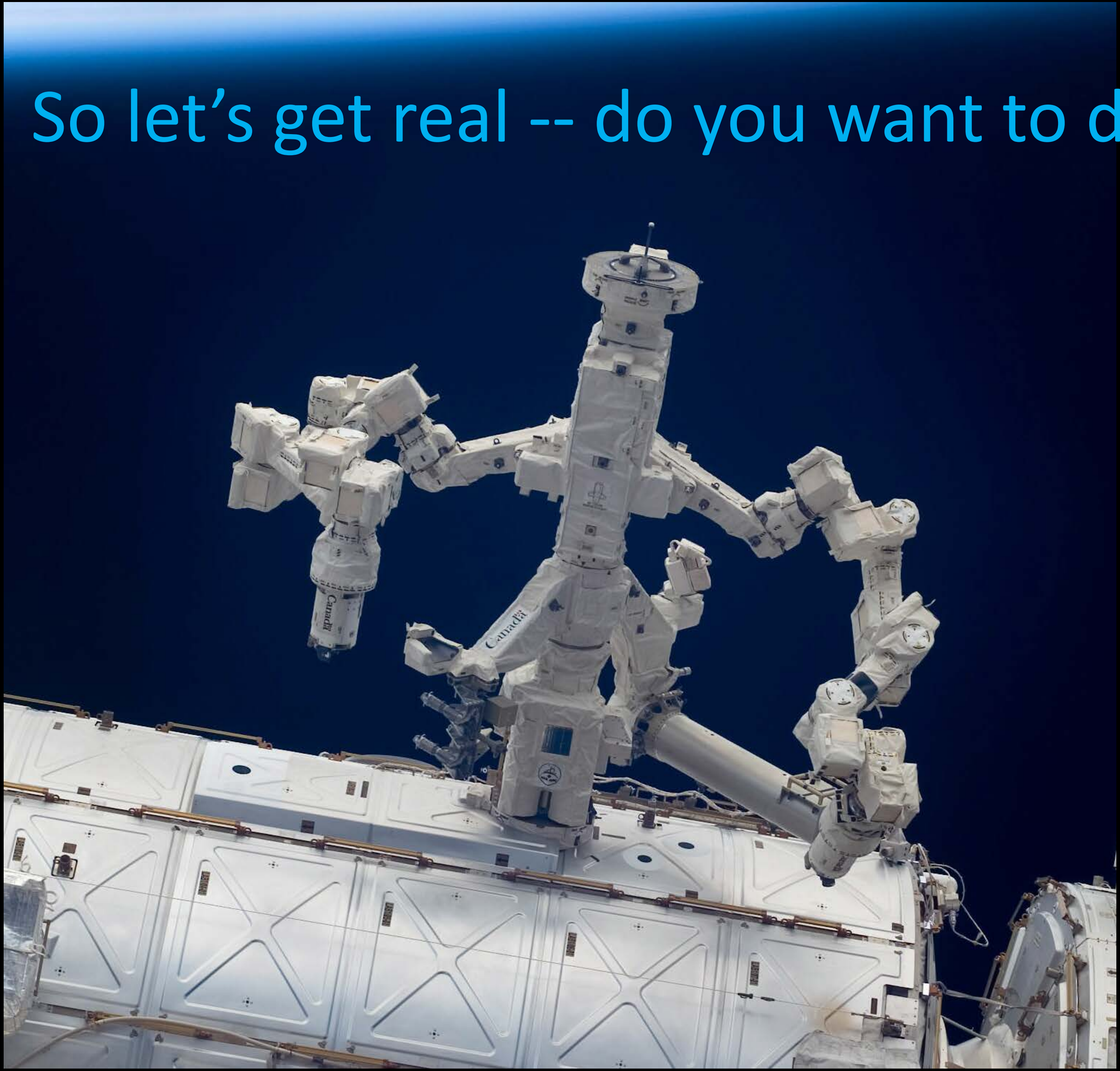


Going to Low Earth Orbit and Beyond . . .

Perhaps even run a starship?

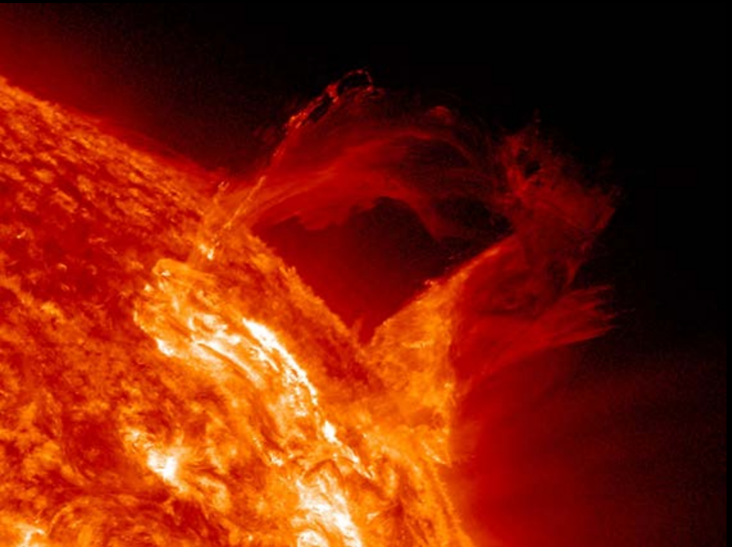


So let’s get real -- do you want to dance?



DEXTRE is missing something?

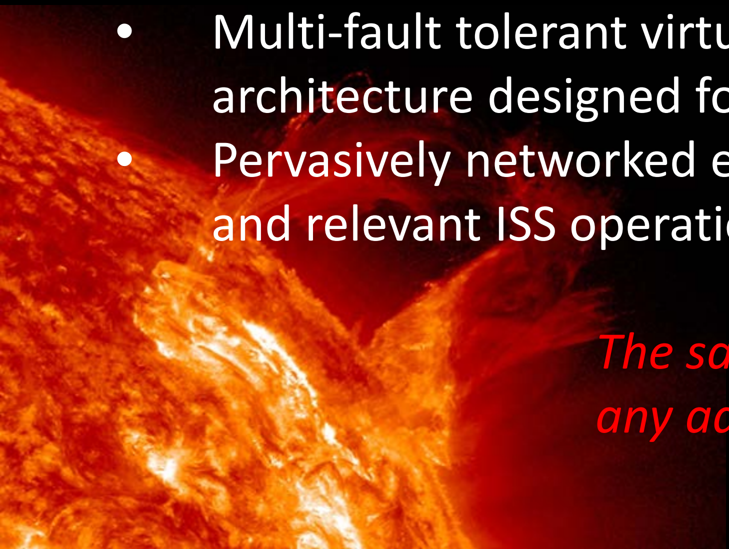
- The Special Purpose Dexterous Manipulator (SPDM) aka DEXTRE was designed to have an Advanced Vision Unit (AVU)
- The AVU was to provide a near realtime state model of the systems-of-systems that made up the SPDM – effectively an autonomic nervous system
- In addition, it would have the ability to dynamically build up a world model of an assigned task area and it’s intersection with the environment
- The combination of these two capabilities with the appropriate sensors/cameras/tags/targets/interfaces and the as-built documentation of the International Space Station was intended to support a mutable locus of control between full teleoperation and full autonomy



The AVU was intended to allow the SPDM to effectively break dance with an EVA astronaut rather making paint drying seem like a spectator sport.

DEXTRE is missing something? - 2

- Alas, it was estimated proximate to 1995 that implementing the AVU as intended would only take 25 times the anticipated available computational capacity of the International Space Station (ISS).
- However, implementing the AVU using 2016 technology should and would be a much more straight forward proposition given . . .
  - Multiple space qualified multi-core thermally managed processors
  - Highly reliable registered Error Correcting Code (ECC) memory
  - Solid state data storage systems
  - Open source multi-threaded operating system amenable to near-realtime operations
  - Multi-fault tolerant virtualizable functions and a generalized control architecture designed for failure tolerance
  - Pervasively networked environment with access to as-built configuration data and relevant ISS operations and environmental data



The same logic is applicable to any EVA/IVA robotics as well any advanced automated system

Making It Real . . .

The order of the problem to be solved must be reduced to something tractable

- Breakup problem space into many sub-problems suitable for parallel processing
- Focus on the sub-problems that matter
- Use boundary conditions, initial conditions, symmetry, known geometry, established datums, etc. to further reduce complexity

The key is to propagate constraints as rapidly as possible

Making It Real . . .

A mutable locus of control is required between:

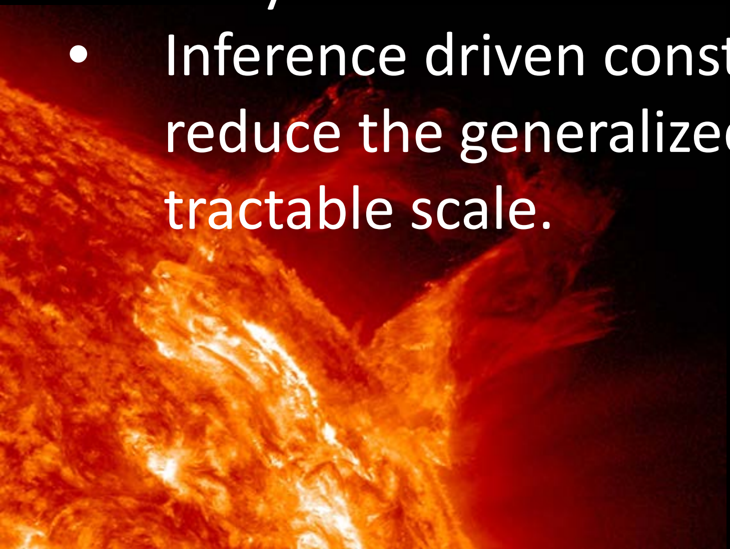
- Teleoperated and Autonomous Operations
- Ground and Inflight Operations
- Scheduled and Dynamic Operations
- Defined and Sensed Environments
- Referenced/Predicted/Sensed Geometry
- Toggled and Shared Control

This necessitates near realtime state models of the involved systems and the environment

Making It Real . . .

- N-Dimensional interaction problems do not have to be intractable.
- With appropriate metadata, transforms can be applied.
  - *Data is a set of ordered symbols*
  - *Information is Data in context*
  - *Knowledge is Information in perspective*
  - *Wisdom is Knowledge in reflection*
- Problems of interest can be recast and structured as:

  (Items(Attributes(Values))) -- LISP transform
- They can then be modeled as a set of process flow problems.
- Inference driven constraint propagation can then be applied to reduce the generalized solution space to a computationally tractable scale.



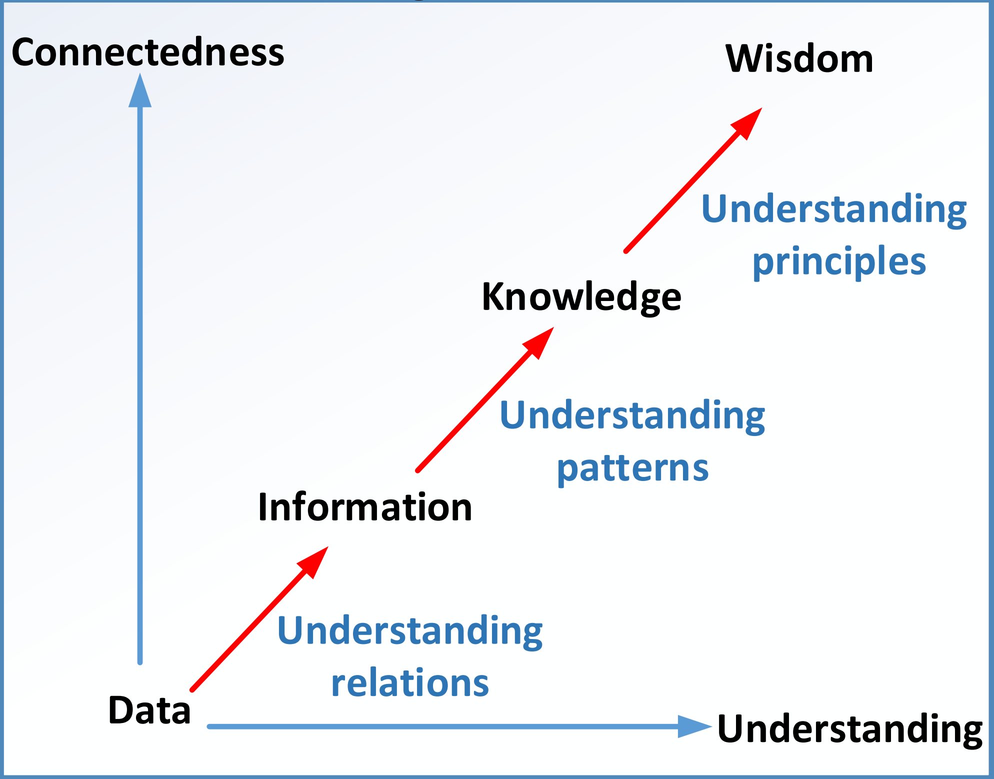
The structure and ordering of knowledge makes a very real difference . . .

Levels of Understanding

Levels of Understanding[6]

- Data is a set of ordered symbols
- Information is Data in Context
- Knowledge is Information in Perspective
- Wisdom is Knowledge in Reflection

The difference between data, information, knowledge and wisdom[7,8,9]



Connectedness

Wisdom

Understanding principles

Knowledge

Understanding patterns

Information

Understanding relations

Data

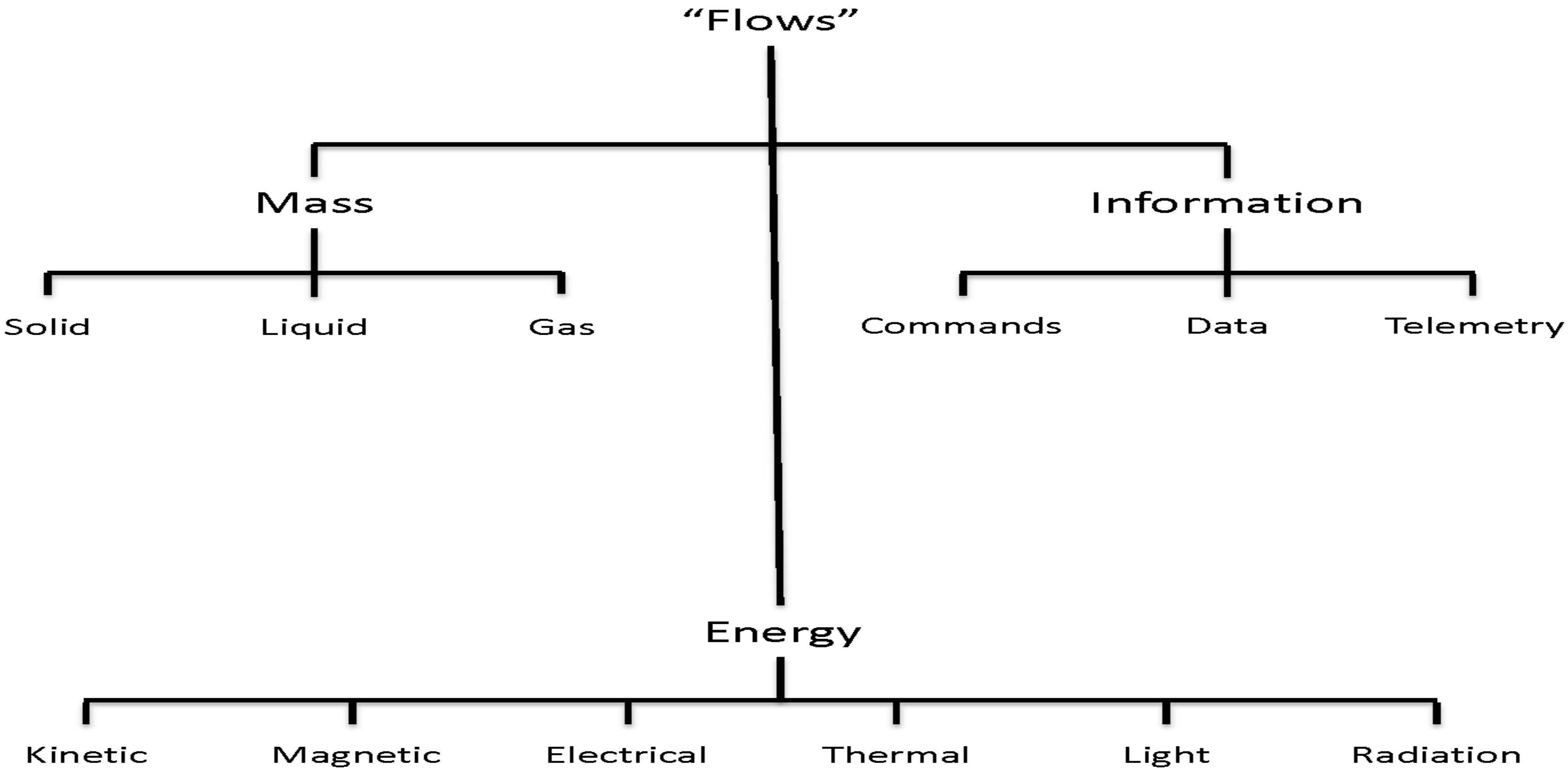
Understanding

Building Near-Realtime State Models . . .

- Systems-of-systems can be bounded as a finite set of state transitions
- Systems can be modeled as a set of flows across defined interfaces
- A taxonomy of flows can be defined as either energy, mass, or information and then further subdivided into individual types
- Each type of flow can be defined by a specific set of qualitative and quantitative attributes, independent of the source and terminus

Each set of characterized flows can be associated with corresponding states and allowable transitions.

Figure 10.
Sub-System "Flow" Taxonomy



"Flows"

Mass

Solid

Liquid

Gas

Information

Commands

Data

Telemetry

Energy

Kinetic

Magnetic

Electrical

Thermal

Light

Radiation

Relevance

- This body of work 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 near realtime state models and the enhanced Management Operations Control Applications that can be brought to fruition.
- XISP-Inc Interoperable Network Communications Architecture – Applications (INCA-A) is a planned guest experimenter on upcoming the NASA Laser Communications Relay Demonstration (LCRD) mission.

MOCA Mission Initial Objectives

1. Defining and prototyping parametric state models for integrated end-to-end mission operations control applications.
2. Implementing the parametric state models for technology development and demonstration mission prototypes, test and flight articles.
3. This effort includes the incremental, iterative, and recursive development of near real-time state models of all the supported mission components operating within the MCT framework/environment

MOCA Initial Products for Supported Missions*

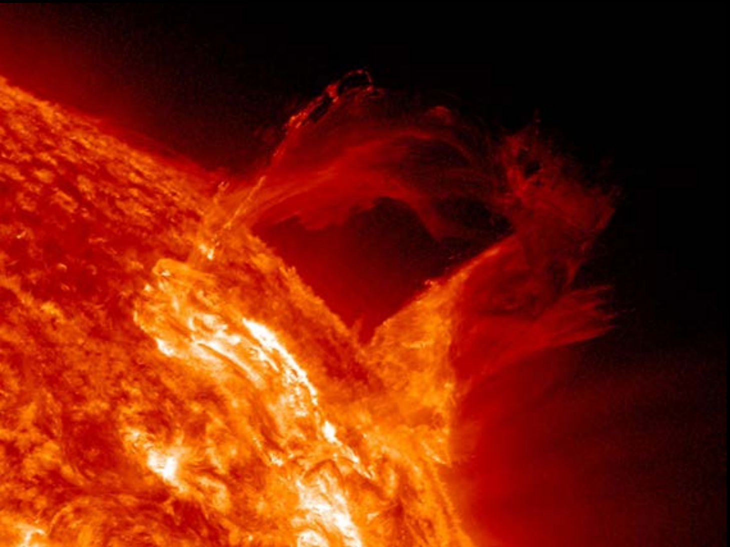
1. Development of a paper model and individual element protocode;
2. Development of functioning individual element models and an end-to-end model protocode;
3. Optimization of individual element models and a functioning end-to-end model;
4. Testing of the optimized end-to-end model and individual element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

** MOCA progress for each supported mission is being driven by the status and schedule of each mission and the availability of resources.*

MOCA Extended Activities

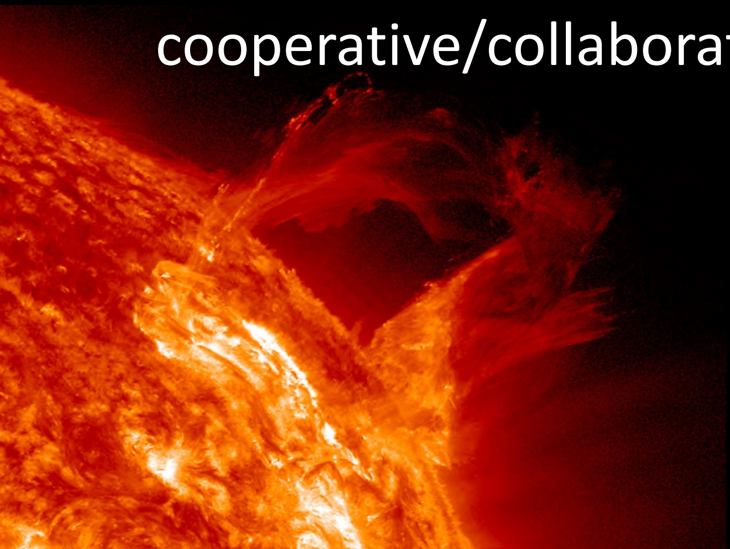
MOCA extended activities will focus on actual on-orbit demonstrations and testing the efficacy of the near realtime parametric state models developed for the supported missions.

Follow-on activities will focus on assessing, reviewing, and establishing the efficacy of applying the near real-time parametric state modelling tools to other current and future technology development missions.



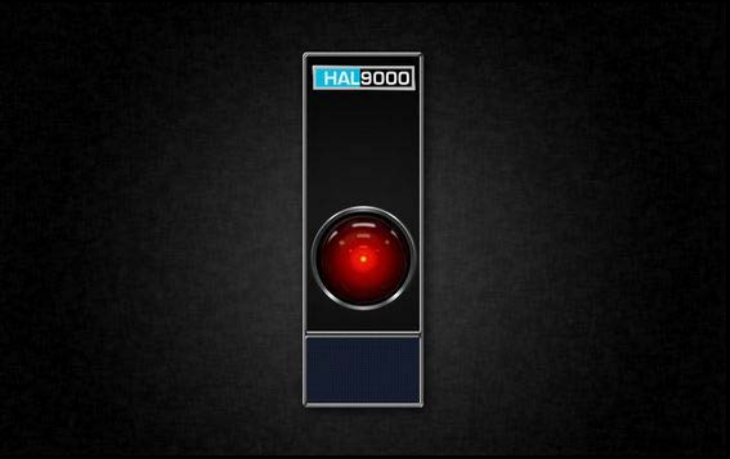
Next Steps

- MOCA is now a commercial mission that will be worked with NASA through a combination of established and proposed Space Act Agreements.
- MOCA is intended to be a foundation for moving forward with multiple new TD^3 missions including AVaTAR mission
- 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.



Reality Check

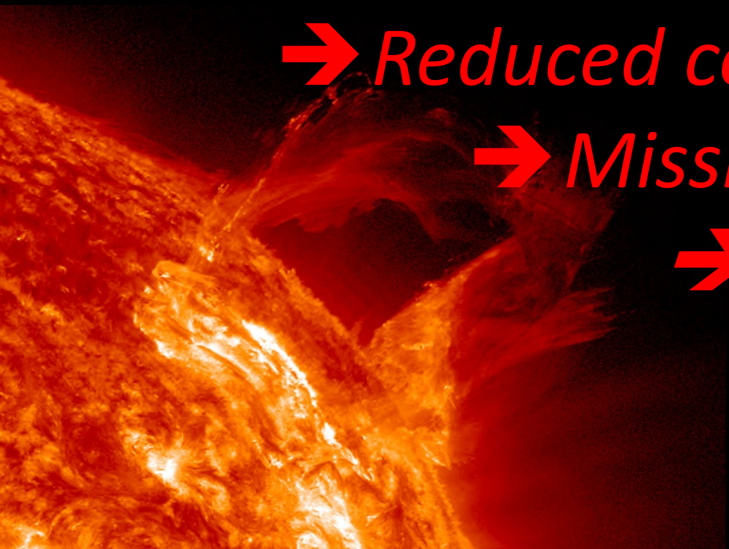
- Reducing the number of perceived “impossible things that have to be accepted before breakfast”* is a way of incrementally disabusing people of unfounded notions.
- Doing something real with the technology that is of demonstrable value can help to establish the confluence of interests necessary to mature the technology for more advanced applications.



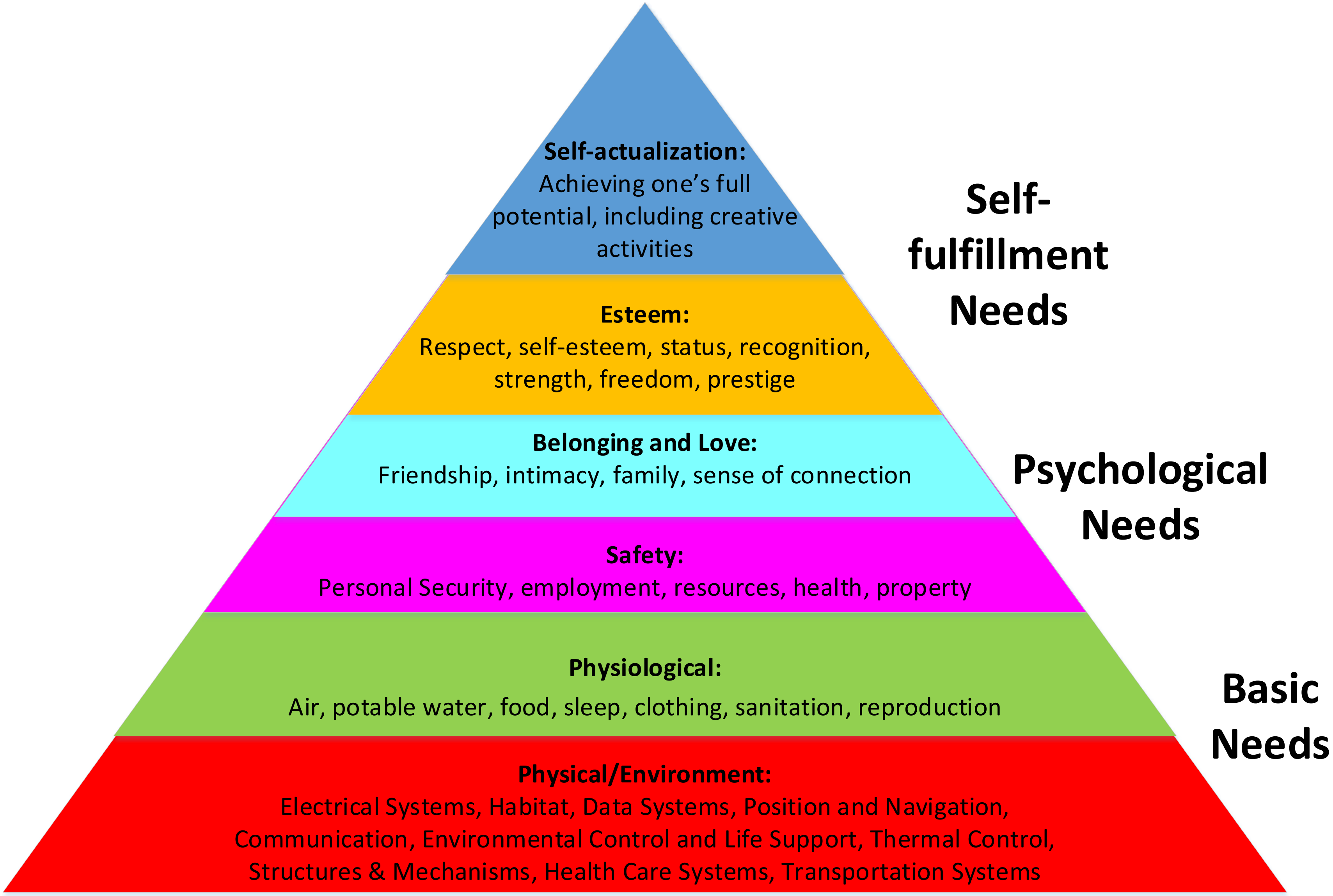
* Allusion to “Alice in Wonderland” by Lewis Carroll. "Alice laughed: "There's no use trying," she said; "one can't believe impossible things."
"I daresay you haven't had much practice," said the Queen. "When I was younger, I always did it for half an hour a day. Why, sometimes I've believed as many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

Conclusion ➔ Technology “Push”

- An incremental investment in the development of near realtime state modelling capabilities that meet real mission requirements can serve as a foundational technology for evolving space automation and robotics capabilities.
- *This work can deliver:*
  - ➔*Reduced cost, schedule & technical risk*
    - ➔*Mission enhancing technology*
      - ➔*Mission enabling technology*



Maslow's Hierarchy of Human Needs[5] updated for Cislunar Settlement



Self-actualization:
Achieving one's full potential, including creative activities

Esteem:
Respect, self-esteem, status, recognition, strength, freedom, prestige

Belonging and Love:
Friendship, intimacy, family, sense of connection

Safety:
Personal Security, employment, resources, health, property

Physiological:
Air, potable water, food, sleep, clothing, sanitation, reproduction

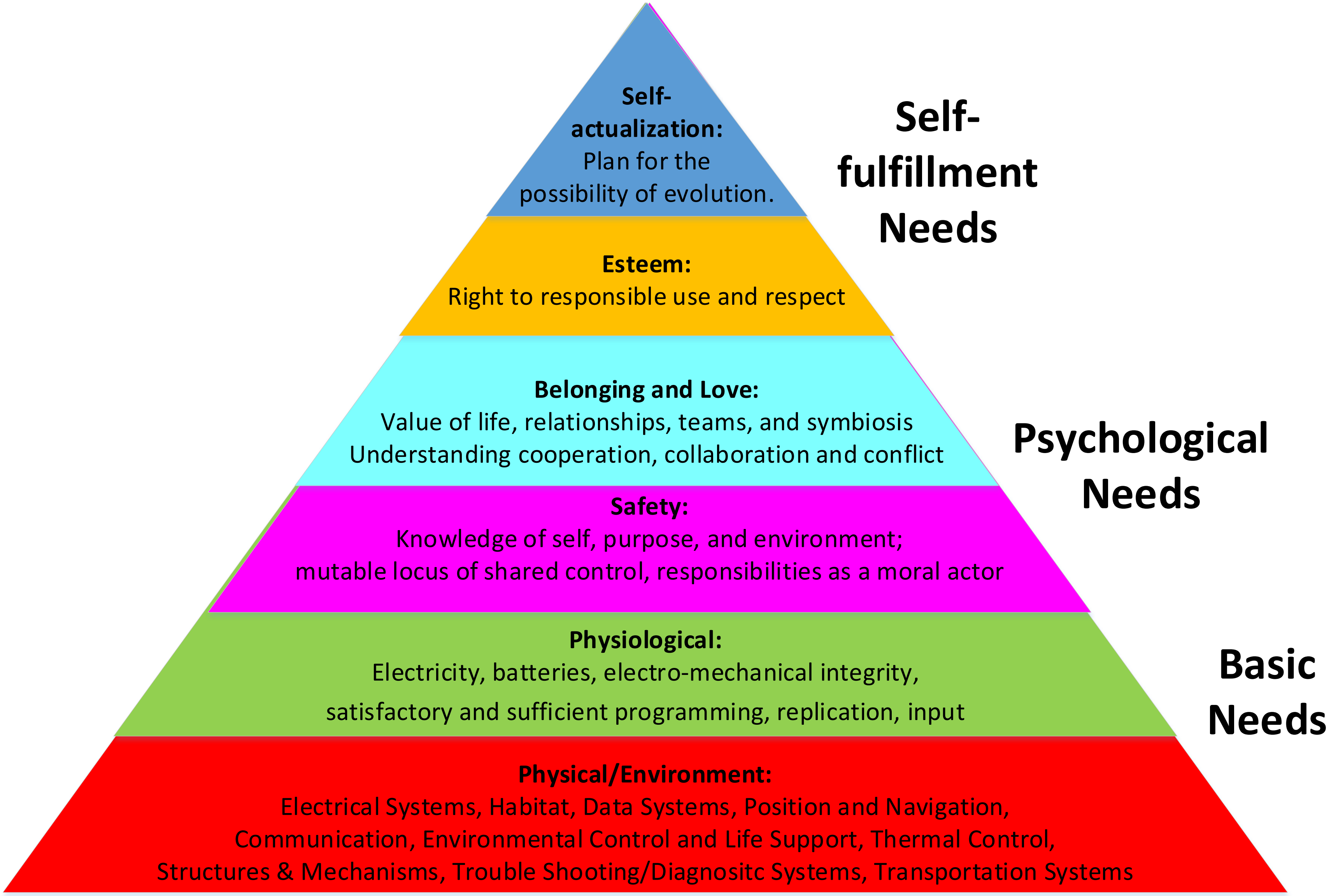
Physical/Environment:
Electrical Systems, Habitat, Data Systems, Position and Navigation, Communication, Environmental Control and Life Support, Thermal Control, Structures & Mechanisms, Health Care Systems, Transportation Systems

Self-fulfillment Needs

Psychological Needs

Basic Needs

Barnhard's Hierarchy of Needs Analog for robotics and advanced autonoma



Self-actualization:
Plan for the possibility of evolution.

Esteem:
Right to responsible use and respect

Belonging and Love:
Value of life, relationships, teams, and symbiosis
Understanding cooperation, collaboration and conflict

Safety:
Knowledge of self, purpose, and environment;
mutable locus of shared control, responsibilities as a moral actor

Physiological:
Electricity, batteries, electro-mechanical integrity,
satisfactory and sufficient programming, replication, input

Physical/Environment:
Electrical Systems, Habitat, Data Systems, Position and Navigation,
Communication, Environmental Control and Life Support, Thermal Control,
Structures & Mechanisms, Trouble Shooting/Diagnositc Systems, Transportation Systems

Self-fulfillment Needs

Psychological Needs

Basic Needs

Conclusion ➔ Mission Requirements “Pull”

- Creating a foundation for a mutable locus of shared control is an investment in a positive future, not a dystopian one.
- How we come to own our own choices, to take responsibility for our own actions, to being stewards for life as we come to understand it, will be defining for our species.
- In the near term our success in building a symbiotic relationship between humans and autonoma will be a key driver in the development of Cislunar space.
- In the long term our success in same could prove to be a determining factor in the fate of our species.

Space-to-Space Power Beaming (SSPB)

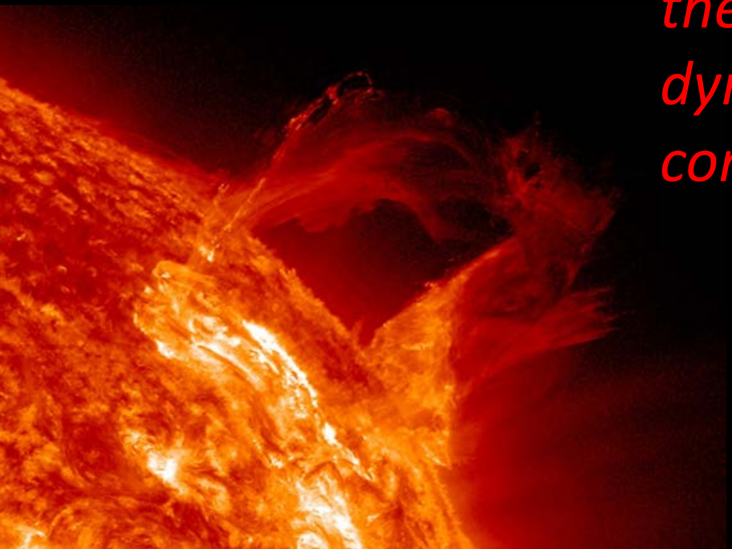
- SSPB provides TD^3 radiant energy beaming testbed, and electrical as well as other utilities (Comm, Nav, etc.) as applicable for ACS, HTA, INCA, and MOCA
- SSPB retire real and perceived technical, cost, and schedule risk associated with radiant energy beaming utilities
- SSPB mission evolution supports ISS co-orbiting free-flyers, Earth facing platforms and/or fractionated systems with LEO/MEO/GEO power augmentation and alternate bus systems, Cis-lunar and lunar surface operations, asteroidal assay mission operations and propulsion augmentation.

➔ *SSPB forges a TD^3 path to Space-to-Space and Space-to-Alternate surface electrical, communications, and navigation utilities.*

➔ *SSPB work is intended to be frequency agnostic from Ka band through optical.*

Mission Operations Control Applications (MOCA)

- MOCA provides TD^3 near realtime state models, mutable locus of control, and virtual operations center for ACS, HTA, INCA, and SSPB
- MOCA facilitates crewed, tele-operated/shared control, and autonomous in situ operations reducing crew time required for experiments and increasing ISS and ground operations productivity.

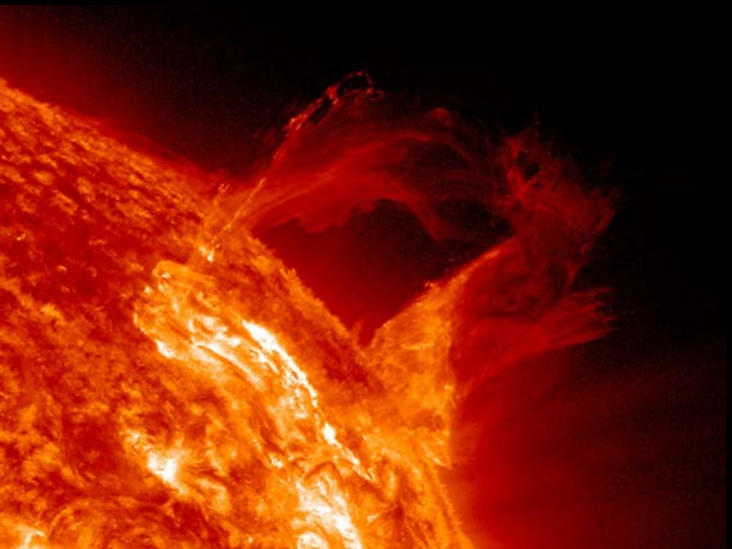


➔ *MOCA can be a resource for furthering the TD^3 of “AutoNAV” and the evolution to dynamically scheduled QoS driven communications and navigation services.*

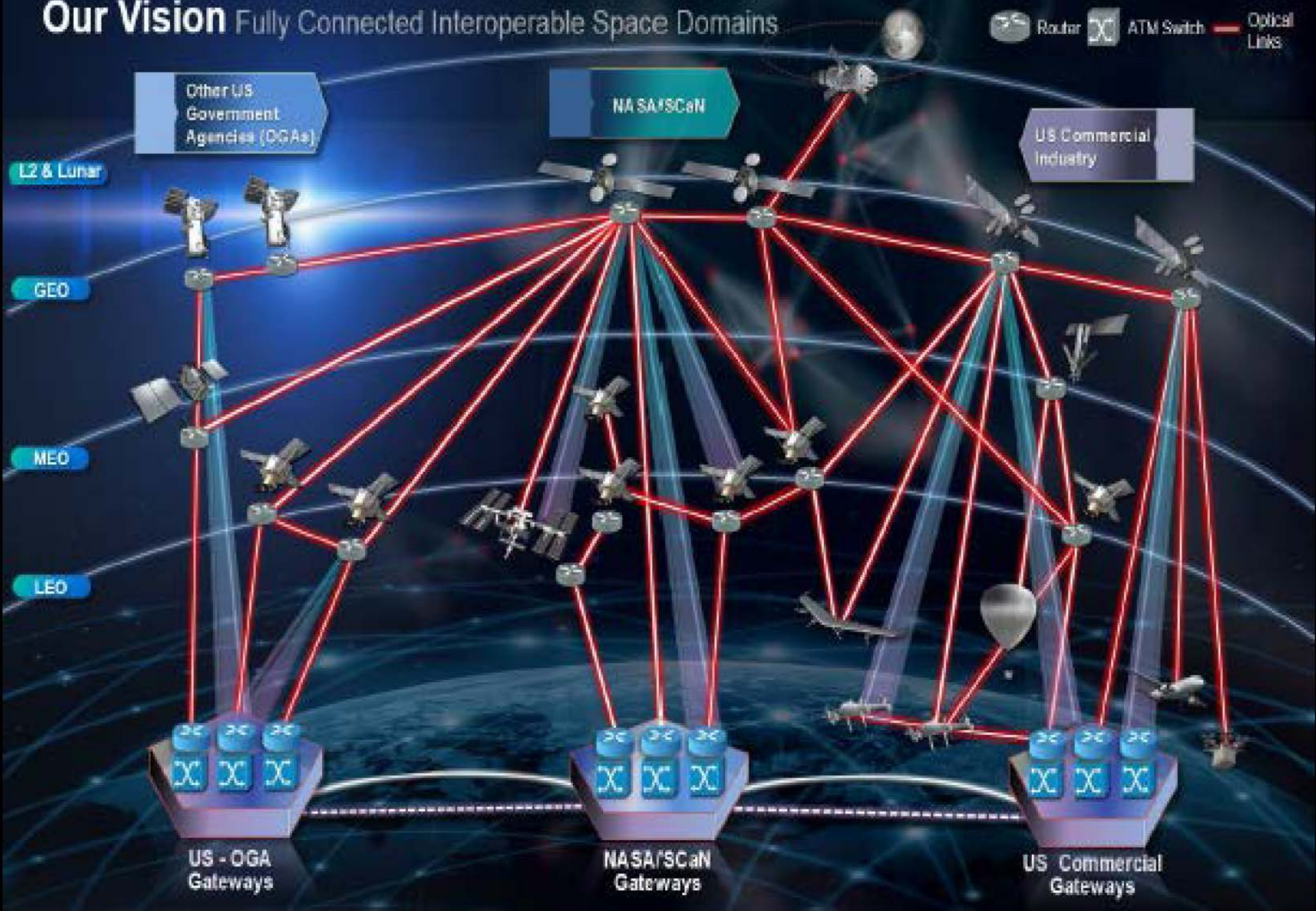
Interoperable Network Communications Architecture (INCA)

INCA elements can support:

- Enhanced automated/autonomous Communications & Navigation state models,
- Dynamically assignable and characterizable resources,
- QoS driven virtualized function support , and
- Cost effective Earth facing, on-orbit, and beyond Earth ad hoc mesh mission support/networks.



Our Vision Fully Connected Interoperable Space Domains

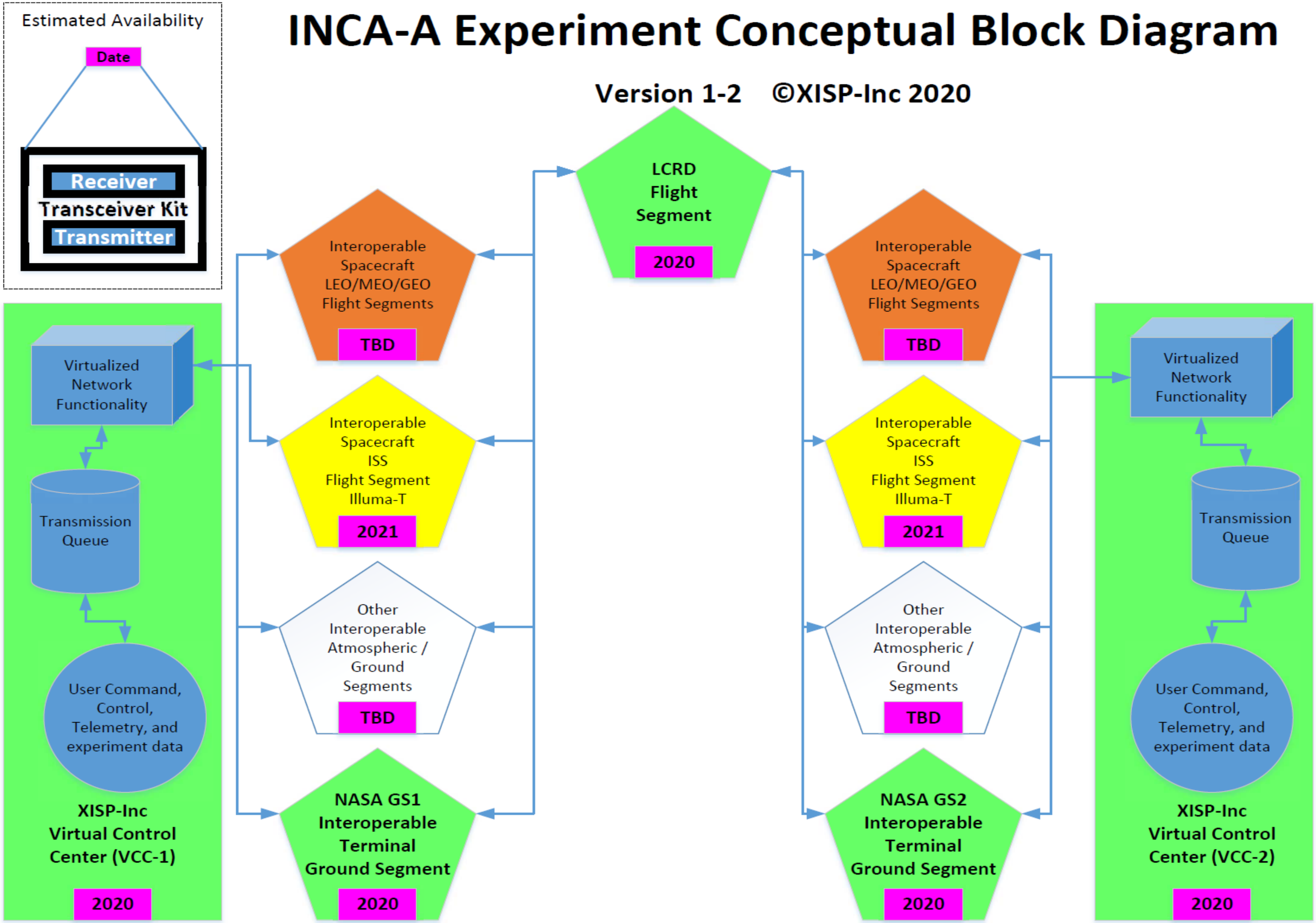


INCA CONSTELLATION

Xtraordinary Innovative
Space Partnerships, Inc

INCA-A Experiment Conceptual Block Diagram

Version 1-2 ©XISP-Inc 2020



Estimated Availability

Date

Receiver

Transceiver Kit

Transmitter

LCRD Flight Segment

2020

Interoperable Spacecraft LEO/MEO/GEO Flight Segments

TBD

Interoperable Spacecraft ISS Flight Segment Illuma-T

2021

Other Interoperable Atmospheric / Ground Segments

TBD

NASA GS1 Interoperable Terminal Ground Segment

2020

NASA GS2 Interoperable Terminal Ground Segment

2020

Virtualized Network Functionality

Transmission Queue

User Command, Control, Telemetry, and experiment data

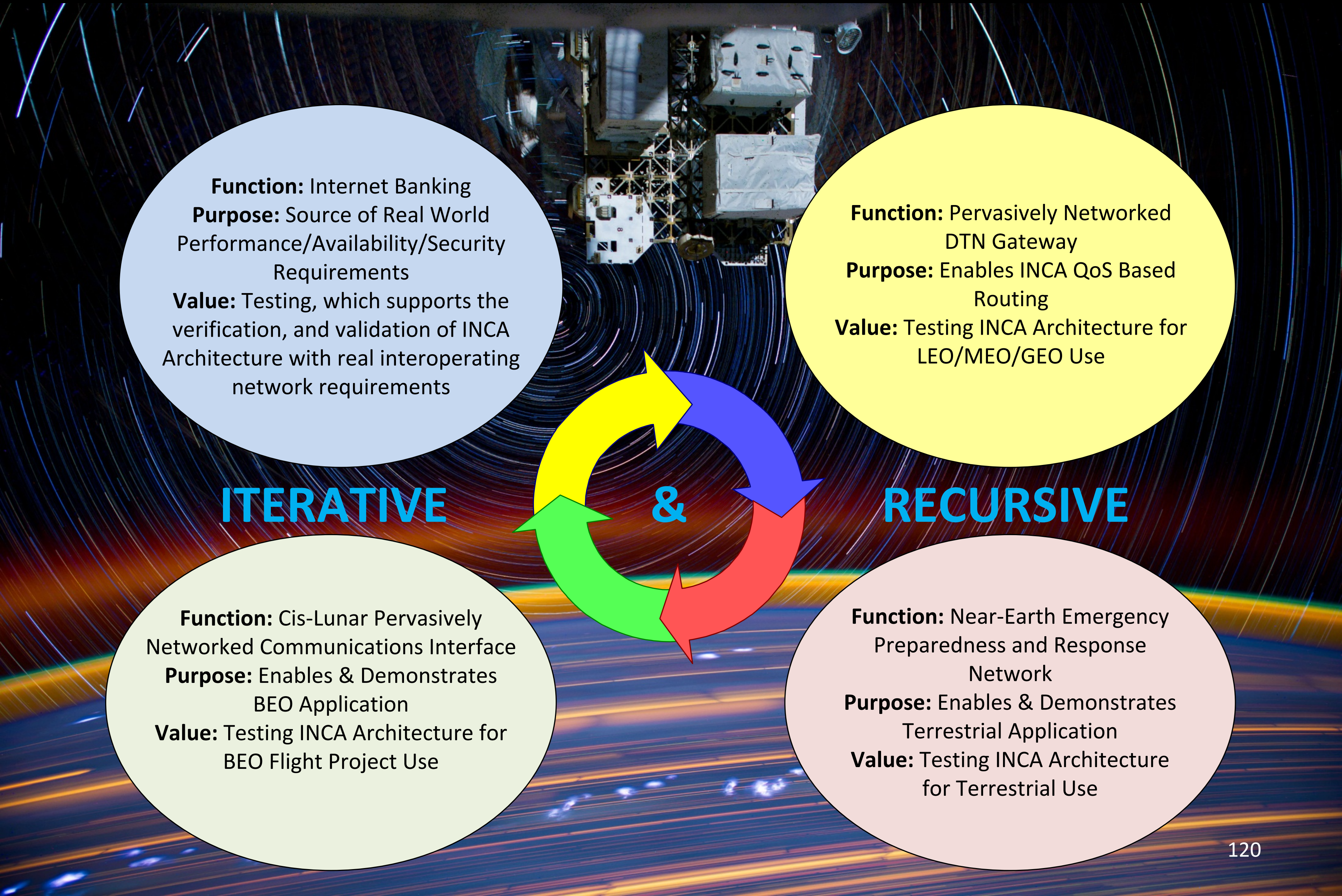
XISP-Inc Virtual Control Center (VCC-1)

2020

XISP-Inc Virtual Control Center (VCC-2)

2020

INCA Experiment Elements



Function: Internet Banking
Purpose: Source of Real World Performance/Availability/Security Requirements
Value: Testing, which supports the verification, and validation of INCA Architecture with real interoperating network requirements

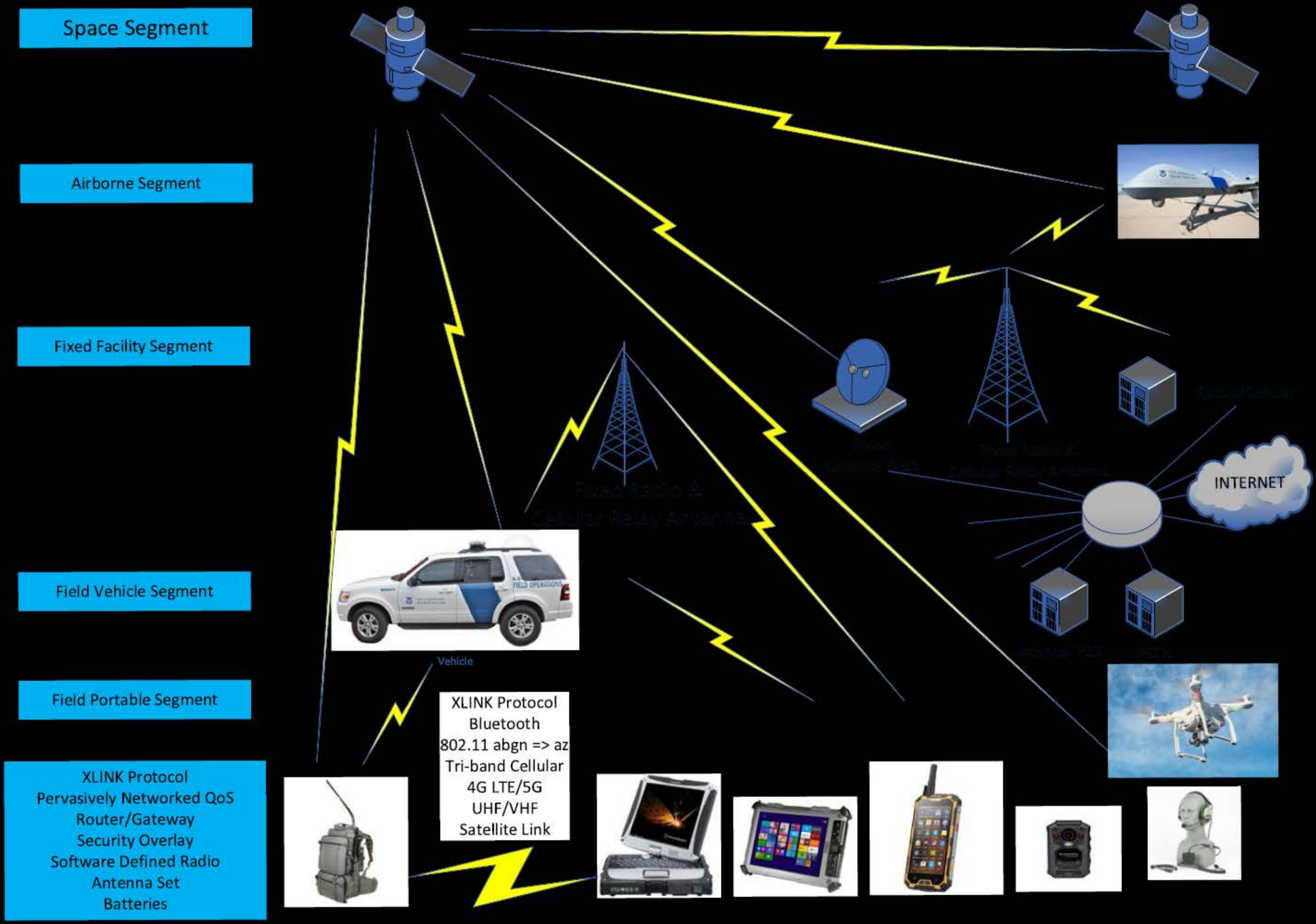
Function: Pervasively Networked DTN Gateway
Purpose: Enables INCA QoS Based Routing
Value: Testing INCA Architecture for LEO/MEO/GEO Use

ITERATIVE & RECURSIVE

Function: Cis-Lunar Pervasively Networked Communications Interface
Purpose: Enables & Demonstrates BEO Application
Value: Testing INCA Architecture for BEO Flight Project Use

Function: Near-Earth Emergency Preparedness and Response Network
Purpose: Enables & Demonstrates Terrestrial Application
Value: Testing INCA Architecture for Terrestrial Use

Figure 1 - Proposed CBP INCA System Preliminary Concept of Operations



Space Segment

Airborne Segment

Fixed Facility Segment

Field Vehicle Segment

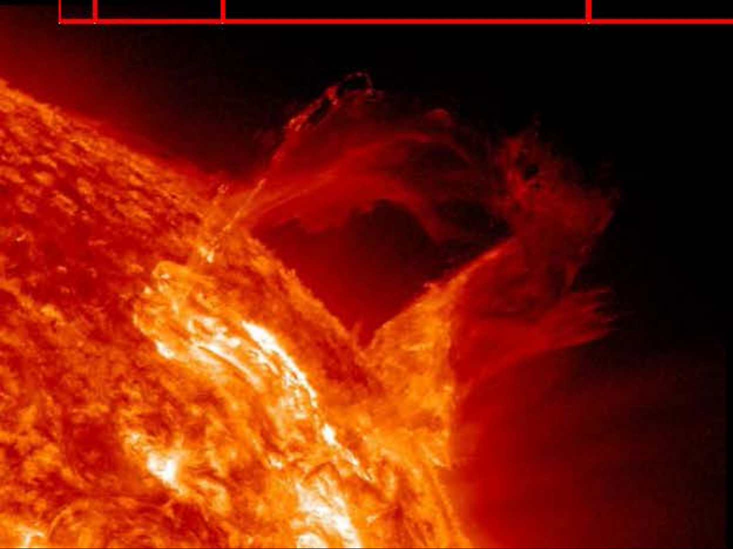
Field Portable Segment

XLINK Protocol
Pervasively Networked QoS
Router/Gateway
Security Overlay
Software Defined Radio
Antenna Set
Batteries

XLINK Protocol
Bluetooth
802.11 abgn => az
Tri-band Cellular
4G LTE/5G
UHF/VHF
Satellite Link

INCA Interface Matrix

			RECEIVE				
			A	B	C	D	E
			Space Segment	Airborne Segment	Fixed Facility Segment	Field Vehicle Segment	Field Portable Segment
TRANSMIT	A	Space Segment	TxA-RxA	TxA-RxB	TxA-RxC	TxA-RxD	TxA-RxE
	B	Airborne Segment	TxB-RxA	TxB-RxB	TxB-RxC	TxB-RxD	TxB-RxE
	C	Fixed Facility Segment	TxC-RxA	TxC-RxB	TxC-RxC	TxC-RxD	TxC-RxE
	D	Field Vehicle Segment	TxD-RxA	TxD-RxB	TxD-RxC	TxD-RxD	TxD-RxE
	E	Field Portable Segment	TxE-RxA	TxE-RxB	TxE-RxC	TxE-RxD	TxE-RxE



XISP-Inc Crosslink Protocol (XLINK)

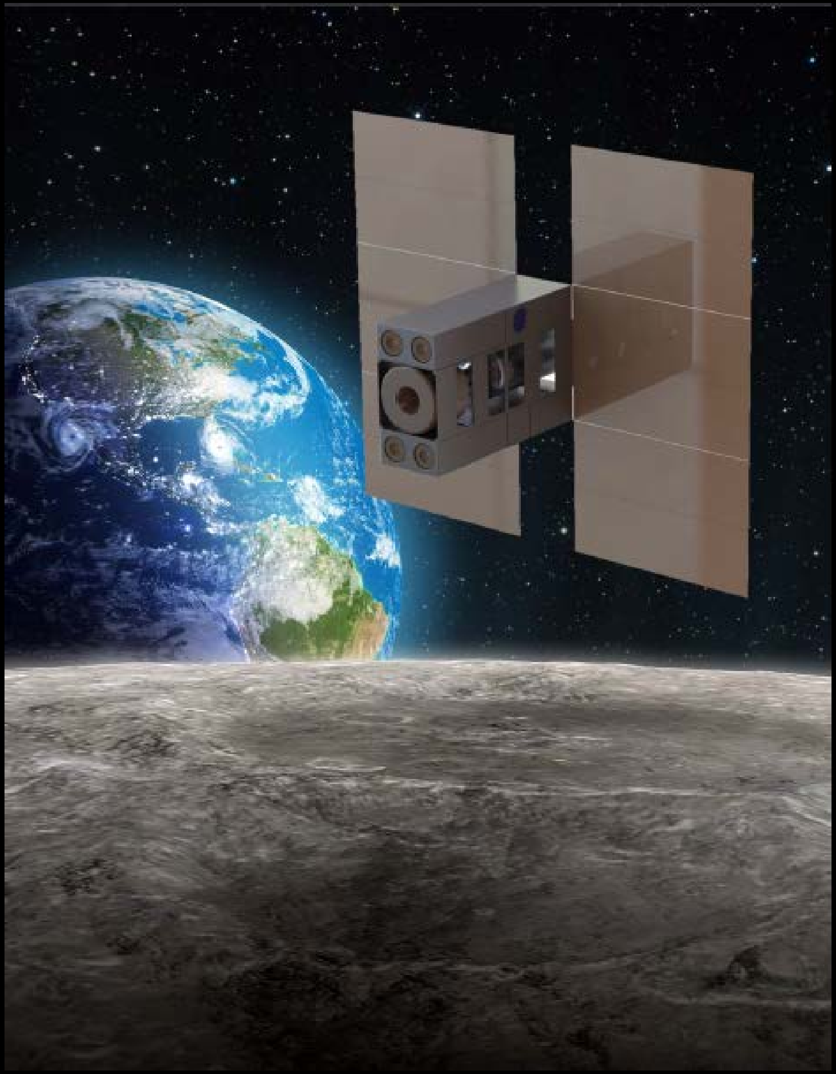
OSI 7 Layer Model	Layer Examples	Pervasively Networked QoS Based Gateway	Input / Output	Process Examples	DOD 4 Layer Model
FUNCTION		Function Models	⇄	State Management	FUNCTION
APPLICATION	End User Layer(s)	Application Models	⇄	DHCP, DNS, FTP, HTTP, IMAP4, POP3, SMTP, SNMP, SSH, NTP	Process / Application
PRESENTATION	Syntax Layer	Presentation Models	⇄	IPSEC/AES – Encrypt/Decrypt	
SESSION	Sync & Send to Ports	Session Models	⇄	DTN – Bundle/Unbundle	
TRANSPORT	TCP	Transport Models	⇄	TCP, UDP	Host-to-Host
NETWORK	Packets	Network Models	⇄	IPv4, IPv6, OSPF, ICMP, IGMP, ARP, RARP, BOOTP	Internet
DATA LINK	Frames	Data Link Models	⇄	802.11, ATM, PPTP, L2TP, 10/100/1000 BaseT, 4/10/40G	Network
PHYSICAL	Physical Structure	Physical Models	⇄	Fiber Optic, Coaxial, Twisted Pair, Space Wire	

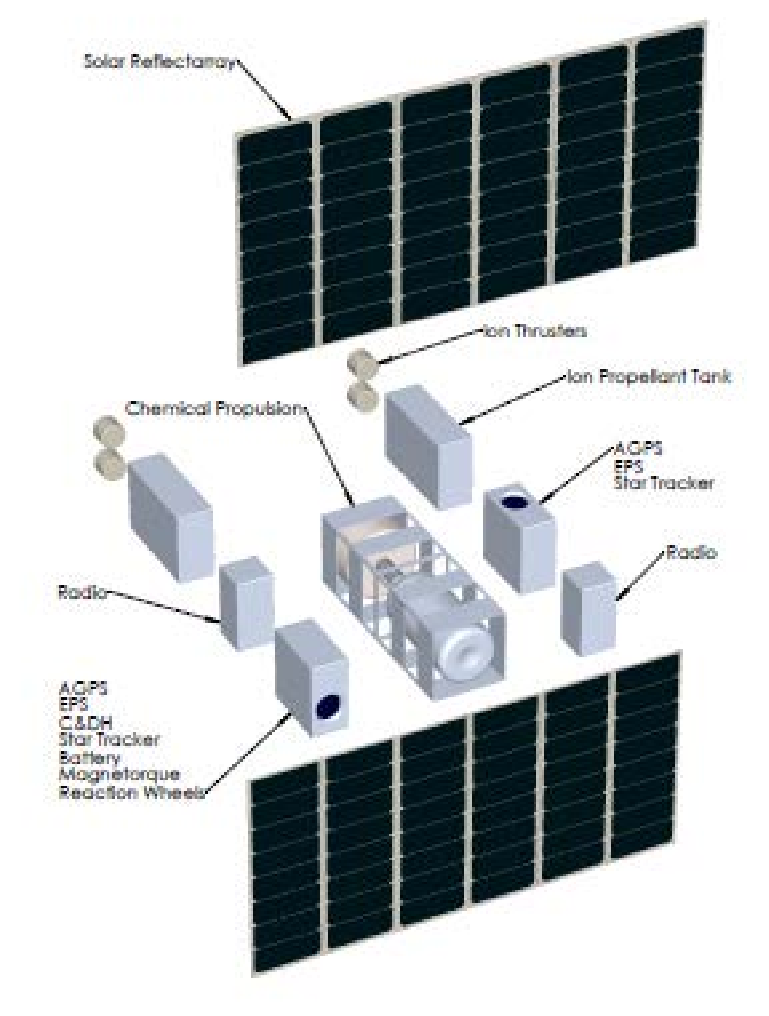
Alpha Cube Satellite (ACS)

- ACS provides a technology development, demonstration, and deployment (TD3) spacecraft bus for HTA, INCA, MOCA, and SSPB
- ACS Low cost highly configurable small spacecraft for Earth facing, Cislunar infrastructure, and beyond Earth orbit applications.
- TD^3 work includes: beyond Earth Orbit SDR through Ka Band and more (W band, laser, etc.), laser retroreflector host and testbed, user hardware & software extensible linux based avionics system (GN&C, ACS, Power, DMS), non-toxic propulsion systems, Virtual Operations Center (based on Open Web MCT & Xrosslink protocol), reflectarray solar/TX&Rx/Rectenna

➔ *ACS is low cost extensible Comm and Nav infrastructure suitable for prototyping applications/services on-orbit, in Cis-lunar space, and beyond.*

Alpha CubeSat Derived Flight Test Articles*

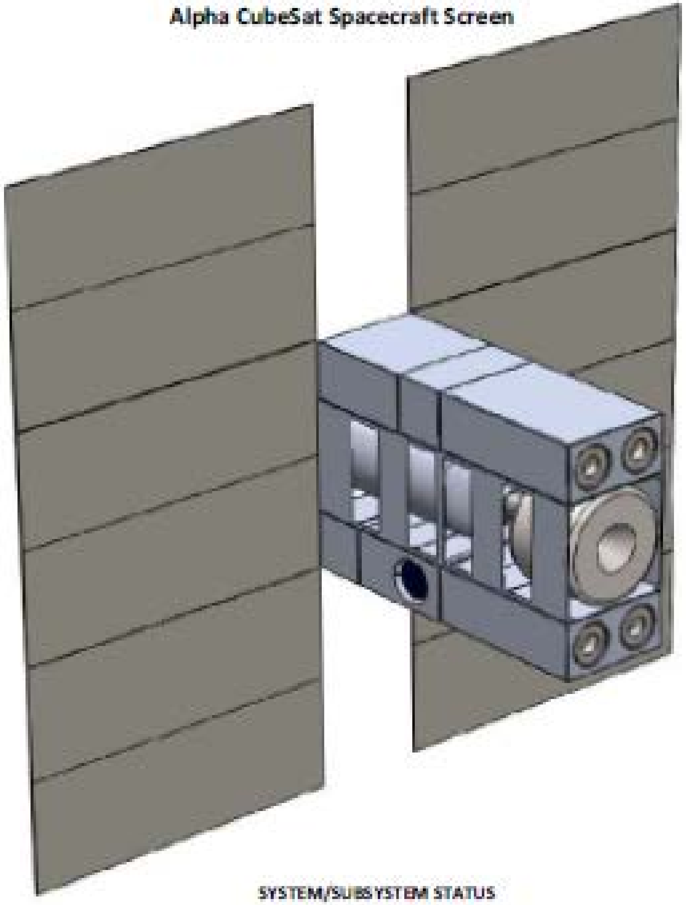




* Alternate 6U flight test article concept derived from NASA CubeQuest Challenge Team Alpha CubeSat design

MANAGEMENT OPERATIONS CONTROL ARCHITECTURE (MOCA) MISSION STATUS

Alpha CubeSat Spacecraft Screen

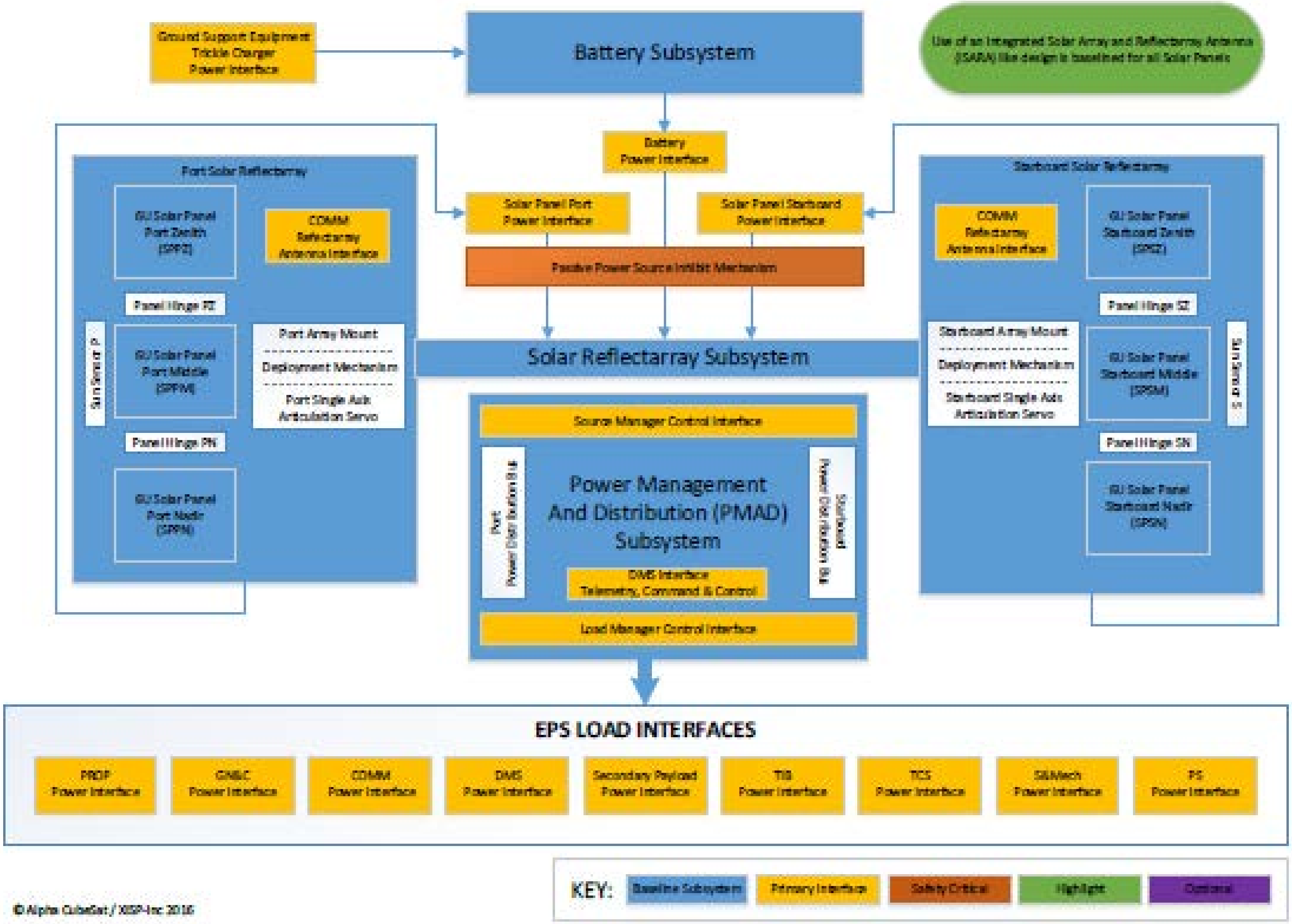


SYSTEM/SUBSYSTEM STATUS

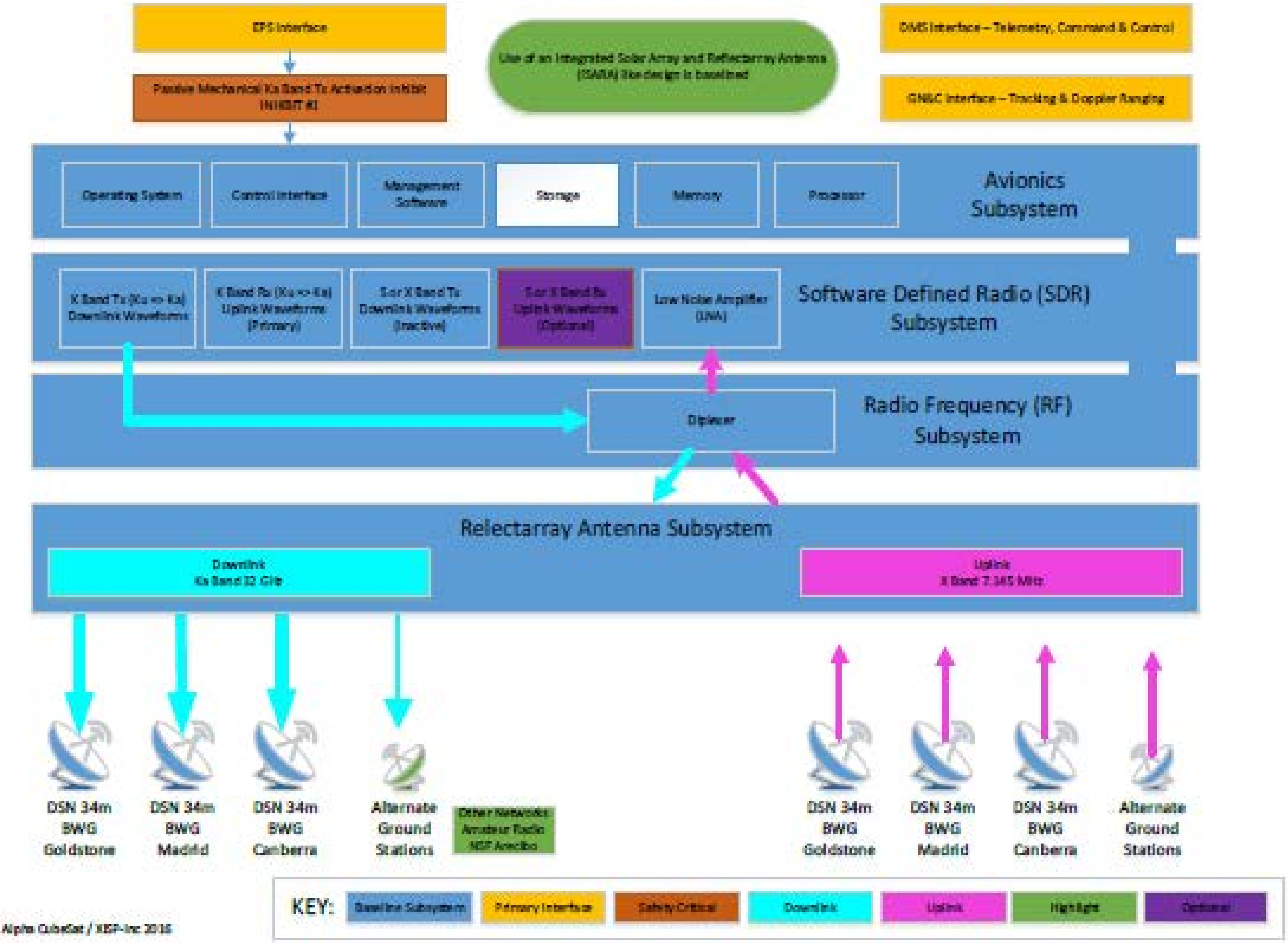
COMM | EPS | DMS | GN&C | S&Mech | PROP | TCS | GS | LSP

PAYLOADS: CUBE QUEST | VENDOR | SCIENCE | MEMORIAL | SPARE | SPARE | SPARE

Alpha CubeSat Electrical Power System (EPS)



Alpha CubeSat Communications System (COMM)



EPS Interface

Passive Mechanical Ka Band Tx Activation Inhibit
INHIBIT #1

Use of an Integrated Solar Array and Reflectarray Antenna (ISARA) like design is baselined

DMS Interface – Telemetry, Command & Control

GN&C Interface – Tracking & Doppler Ranging

Operating System

Control Interface

Management Software

Storage

Memory

Processor

Avionics Subsystem

K Band Tx (Ku <-> Ka) Downlink Waveforms

K Band Rx (Ku <-> Ka) Uplink Waveforms (Primary)

S or X Band Tx Downlink Waveforms (Inactive)

S or X Band Rx Uplink Waveforms (Optional)

Low Noise Amplifier (LNA)

Software Defined Radio (SDR) Subsystem

Diplexer

Radio Frequency (RF) Subsystem

Relectarray Antenna Subsystem

Downlink
Ka Band 32 GHz

Uplink
X Band 7.145 MHz

DSN 34m BWG Goldstone

DSN 34m BWG Madrid

DSN 34m BWG Canberra

Alternate Ground Stations

Other Networks
Amateur Radio
NSF Arecibo

DSN 34m BWG Goldstone

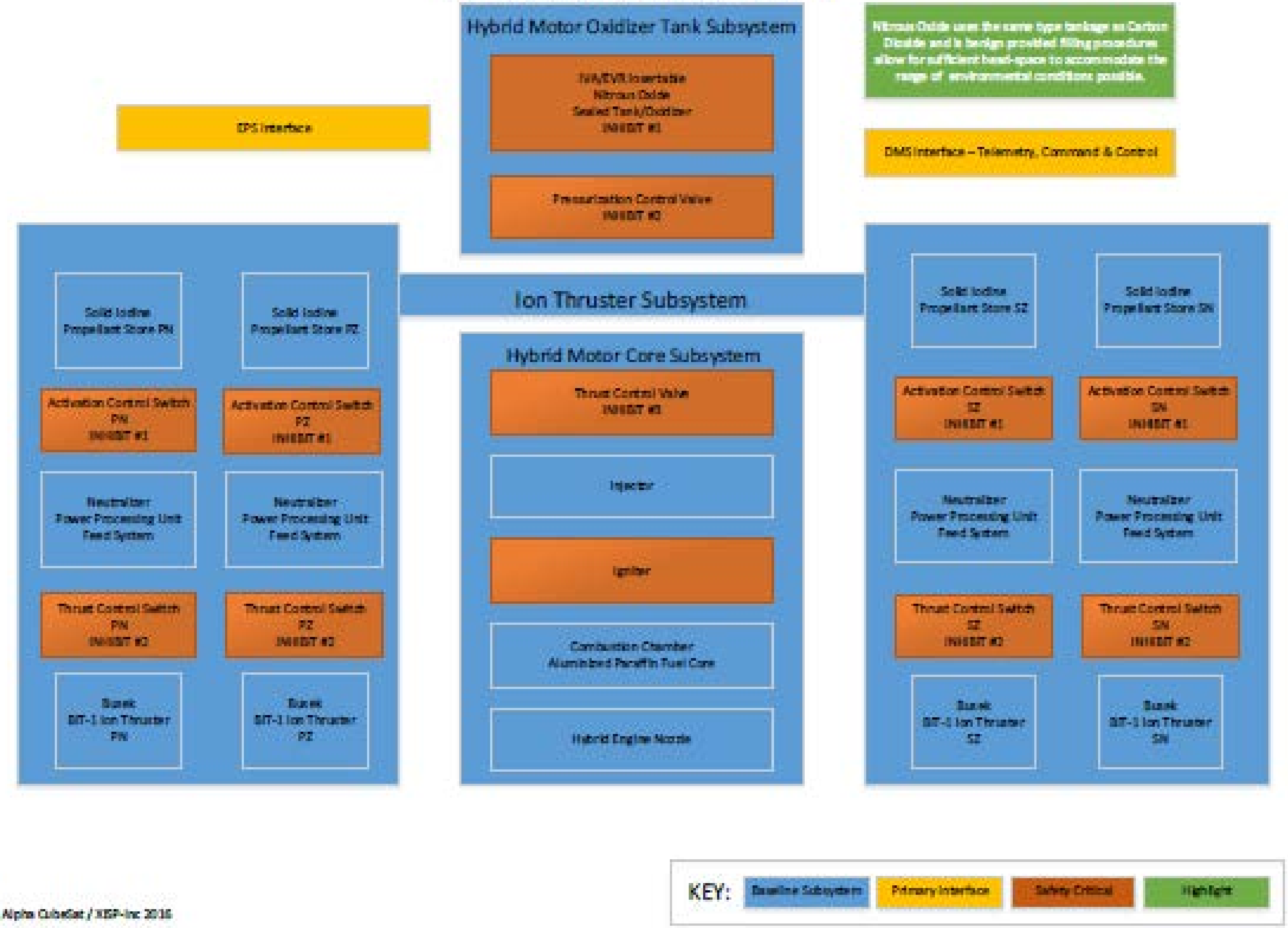
DSN 34m BWG Madrid

DSN 34m BWG Canberra

Alternate Ground Stations

KEY: Baseline Subsystem | Primary Interface | Safety Critical | Downlink | Uplink | Highlight | Optional

Alpha CubeSat Propulsion System (PROP)



Nitrous Oxide uses the same type tankage as Carbon Dioxide and is benign provided filling procedures allow for sufficient head-space to accommodate the range of environmental conditions possible.

EPS Interface

DMS Interface – Telemetry, Command & Control

Hybrid Motor Oxidizer Tank Subsystem

IVA/EVR Insertable
Nitrous Oxide
Sealed Tank/Oxidizer
INHIBIT #1

Pressurization Control Valve
INHIBIT #2

Ion Thruster Subsystem

Solid Iodine
Propellant Store PN

Solid Iodine
Propellant Store PZ

Activation Control Switch
PN
INHIBIT #1

Activation Control Switch
PZ
INHIBIT #1

Neutralizer
Power Processing Unit
Feed System

Neutralizer
Power Processing Unit
Feed System

Thrust Control Switch
PN
INHIBIT #2

Thrust Control Switch
PZ
INHIBIT #2

Busek
BIT-1 Ion Thruster
PN

Busek
BIT-1 Ion Thruster
PZ

Hybrid Motor Core Subsystem

Thrust Control Valve
INHIBIT #3

Injector

Igniter

Combustion Chamber
Aluminized Paraffin Fuel Core

Hybrid Engine Nozzle

Solid Iodine
Propellant Store SZ

Solid Iodine
Propellant Store SN

Activation Control Switch
SZ
INHIBIT #1

Activation Control Switch
SN
INHIBIT #1

Neutralizer
Power Processing Unit
Feed System

Neutralizer
Power Processing Unit
Feed System

Thrust Control Switch
SZ
INHIBIT #2

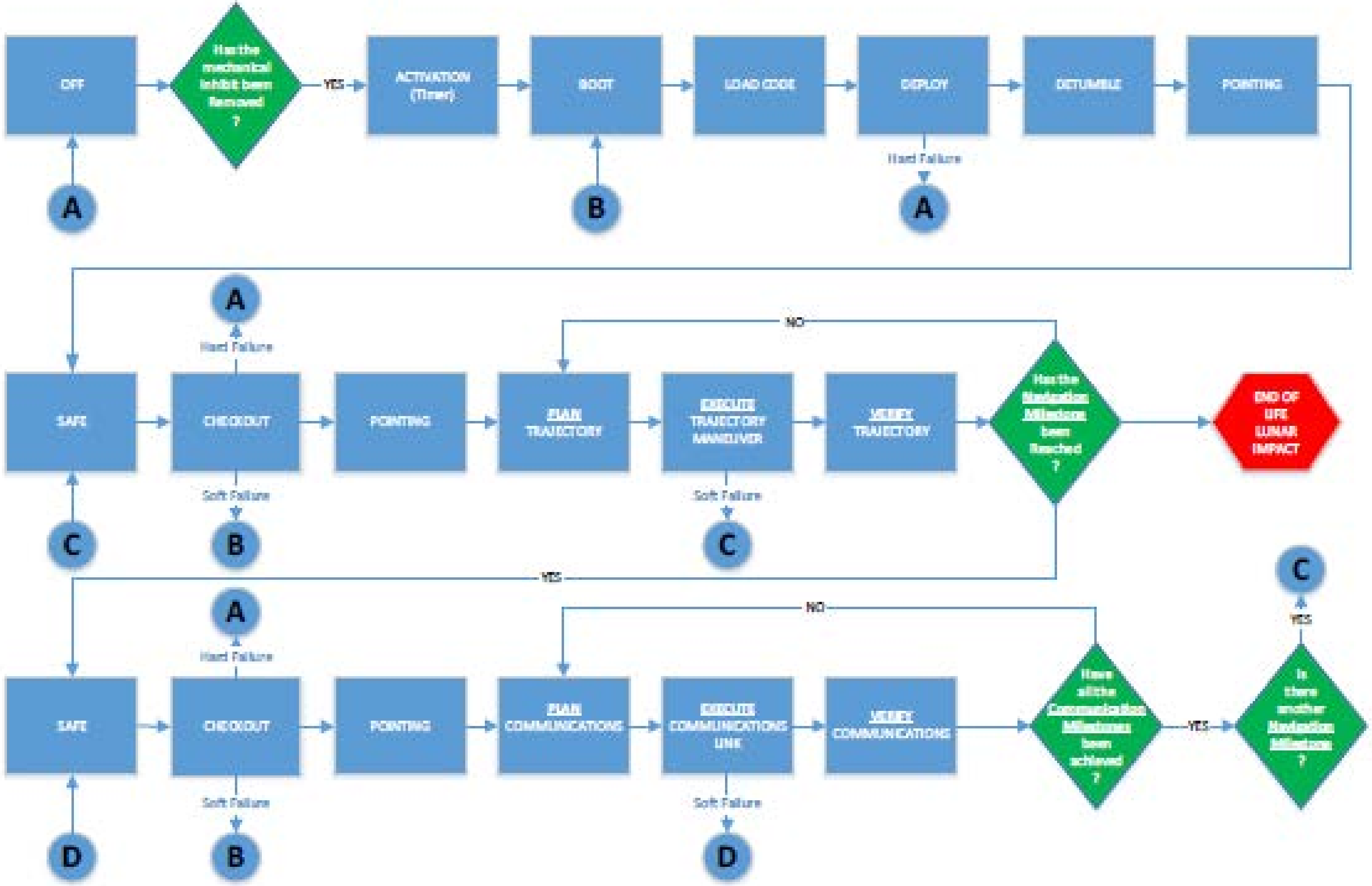
Thrust Control Switch
SN
INHIBIT #2

Busek
BIT-1 Ion Thruster
SZ

Busek
BIT-1 Ion Thruster
SN

KEY: Baseline Subsystem | Primary Interface | Safety Critical | Highlight

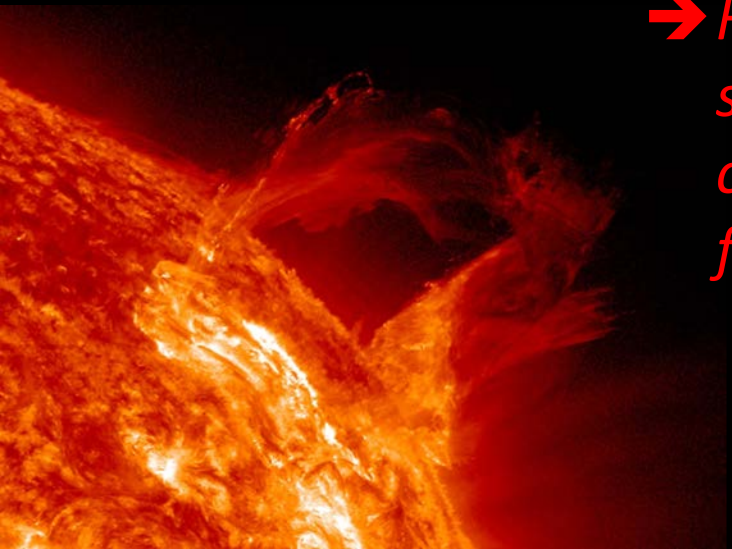
Alpha CubeSat Mode / State Transitions

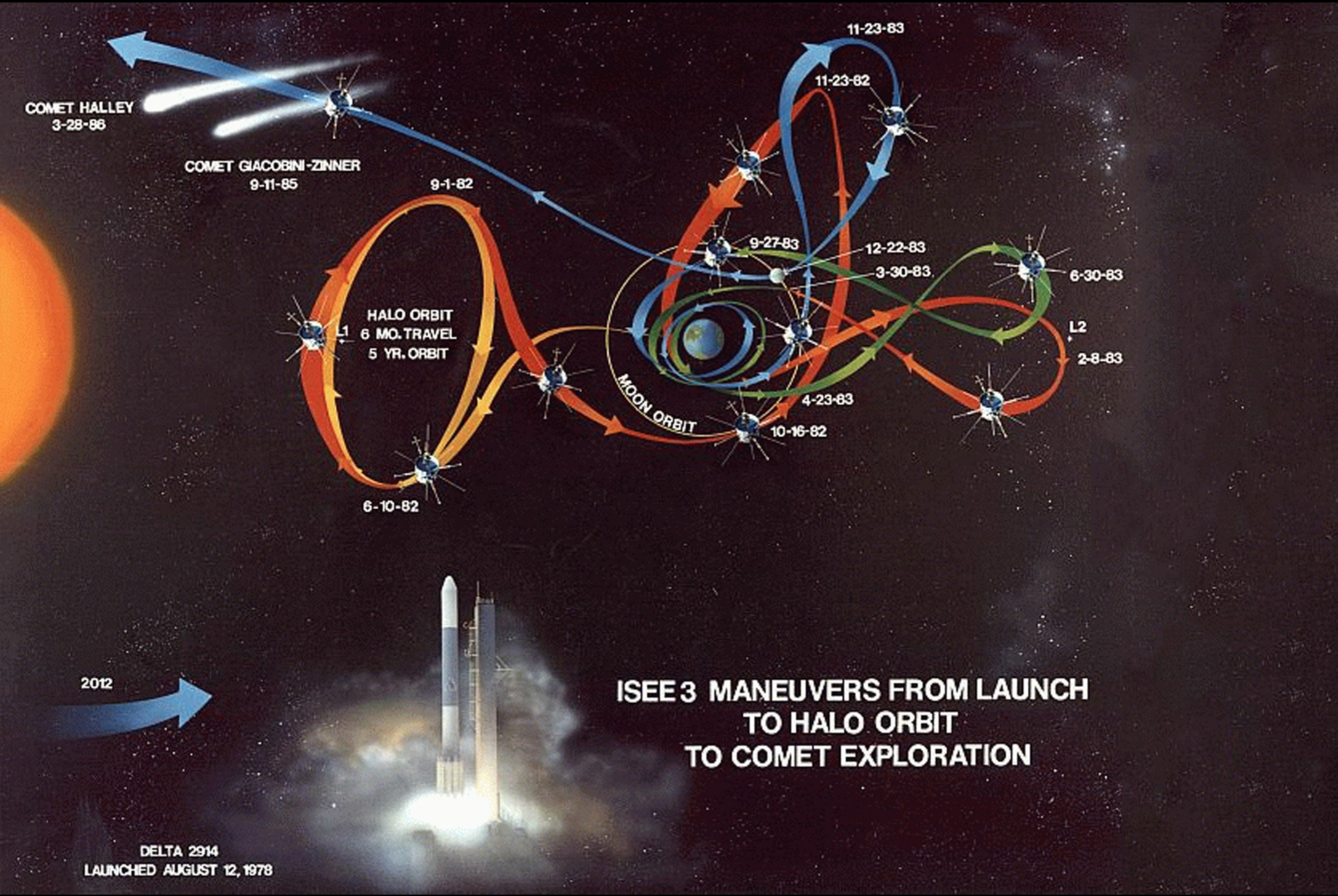


Halfway To Anywhere (HTA)

- HTA provides TD^3 propulsion testbed, trajectory insertion bus, alternate minimum energy trajectories, and resonance orbits for ACS, INCA, MOCA and SSPB.
- *HTA leads to the use of ISS as a transportation node for low cost, readily deployable Earth orbit, cislunar and beyond Earth orbit mission support.*

➔ *HTA helps draws out the requirements for space-to-space electrical, communications, and navigation utilities for LEO/MEO/GEO, and beyond.*

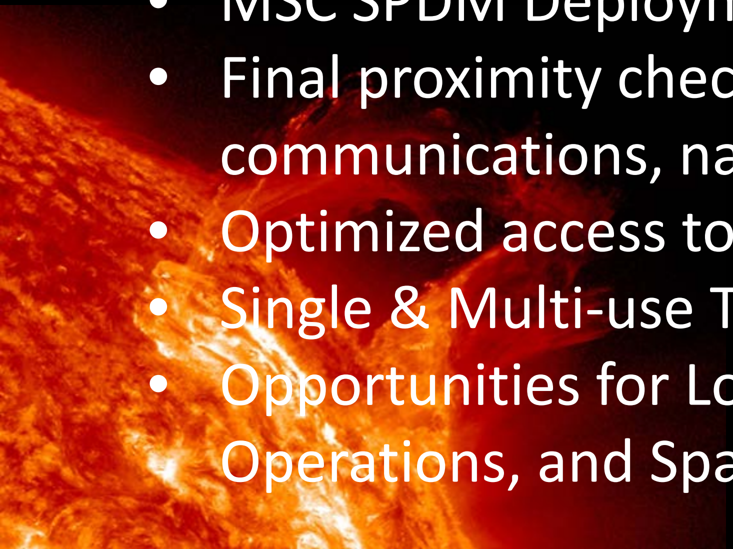




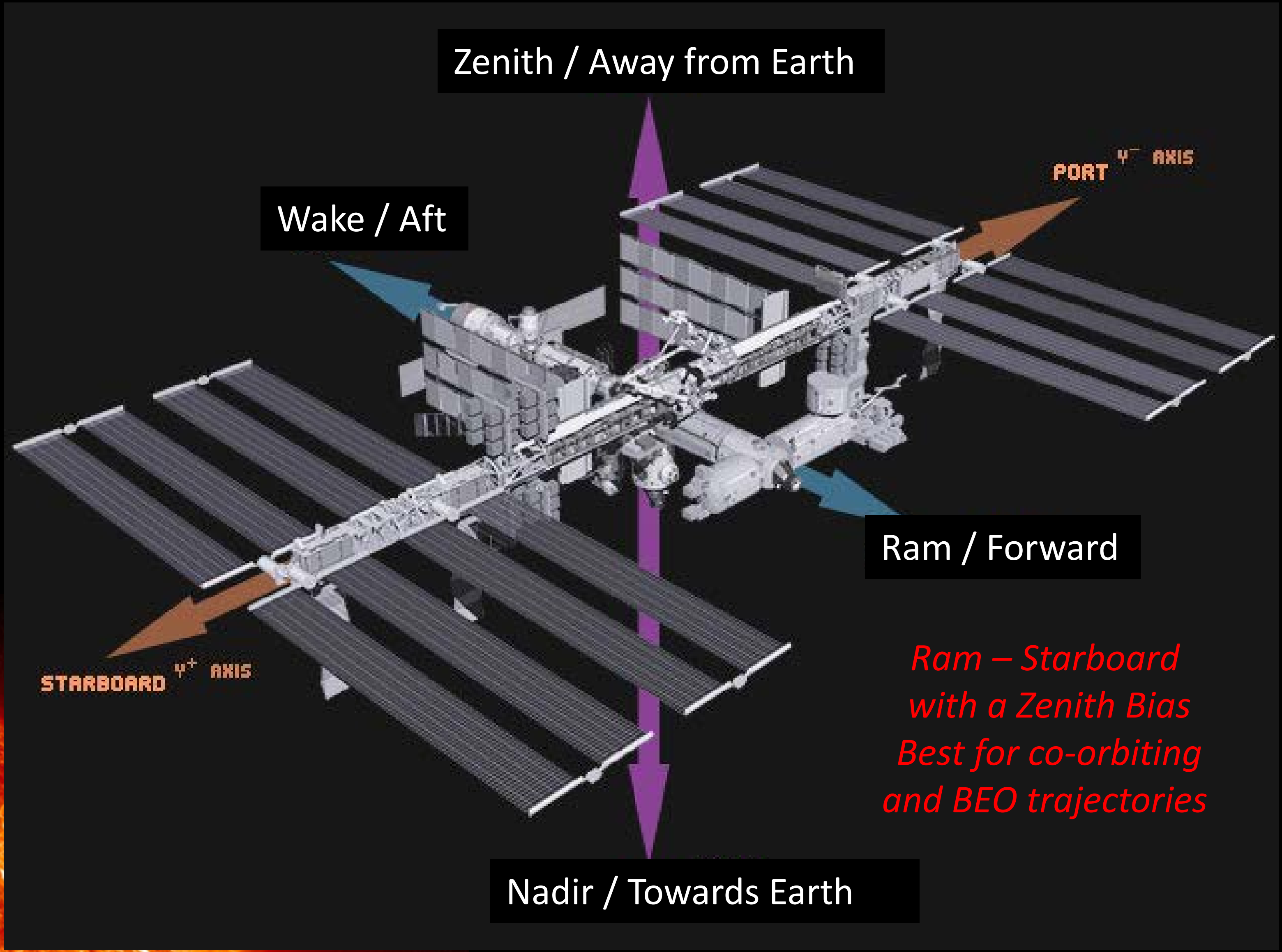
ISEE 3 MANEUVERS FROM LAUNCH
TO HALO ORBIT
TO COMET EXPLORATION

ISS as a Launch Platform - 1

- Commercial Cargo Pressurized “Softpack” launch & stow
  - IVA unpack & final assembly
  - CYCLOPS JEM Airlock IVA → EVR Transition
  - EVR handoff to Mobile Servicing Centre (MSC)
- Commercial Cargo Unpressurized Cargo launch & stow
  - EVR unpack & final assembly
  - EVR handoff to Mobile Servicing Centre (MSC)
- Support services
  - EVR MSC relocate & position for deployment
  - MSC SPDM Deployment RAM + Starboard + Zenith Bias
  - Final proximity checkout services (e.g., imaging, communications, navigation & power)
  - Optimized access to alternative minimum energy trajectories
  - Single & Multi-use Trajectory Insertion Buses
  - Opportunities for Low Cost Earth Applications, Space Operations, and Space Exploration Missions

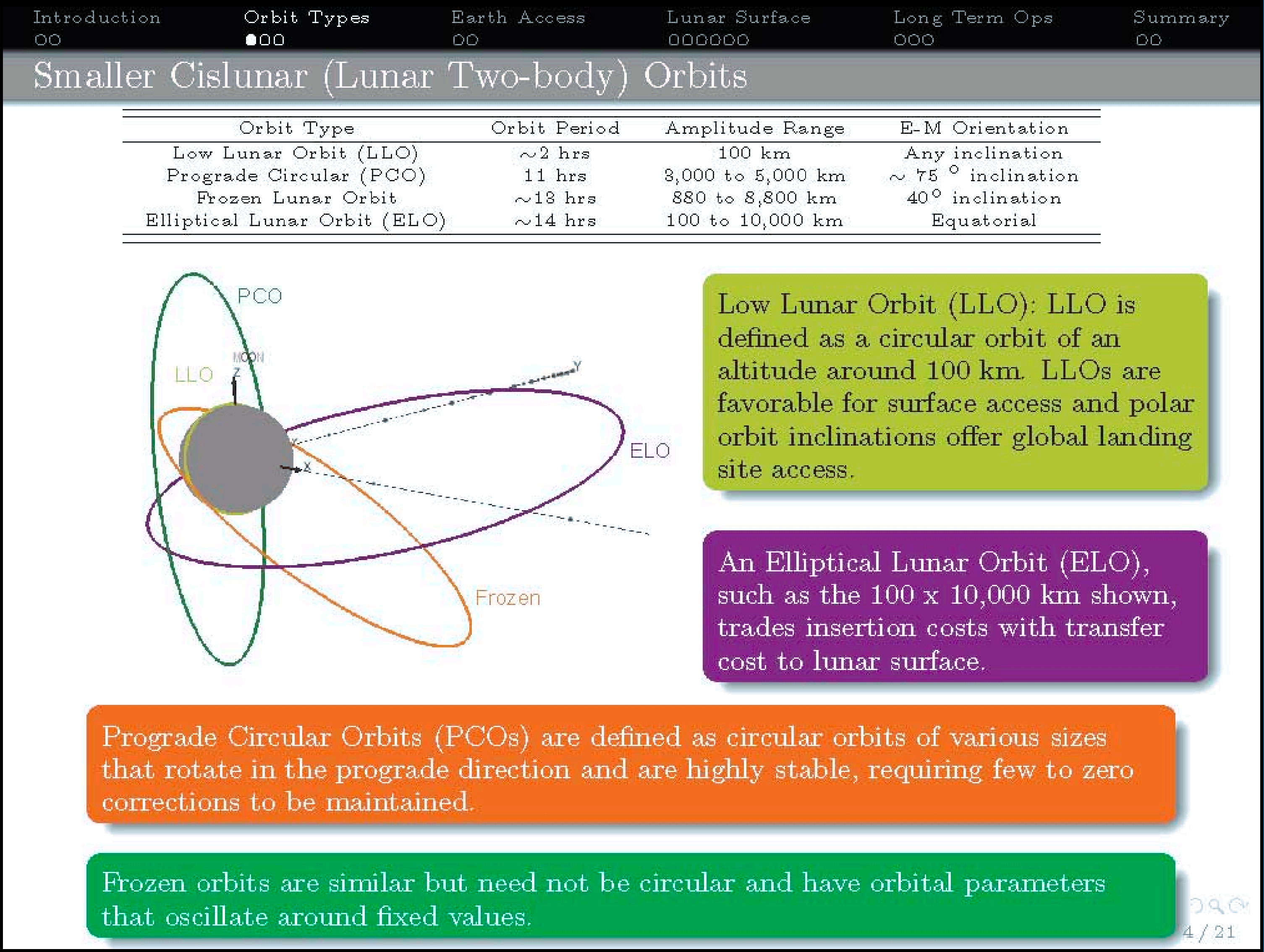


ISS as a Launch Platform - 2



Ram – Starboard
with a Zenith Bias
Best for co-orbiting
and BEO trajectories

LUNAR RESONANCE ORBITS



Smaller Cislunar (Lunar Two-body) Orbits

Orbit Type	Orbit Period	Amplitude Range	E-M Orientation
Low Lunar Orbit (LLO)	∼2 hrs	100 km	Any inclination
Prograde Circular (PCO)	11 hrs	3,000 to 5,000 km	∼ 75 ° inclination
Frozen Lunar Orbit	∼13 hrs	880 to 8,800 km	40° inclination
Elliptical Lunar Orbit (ELO)	∼14 hrs	100 to 10,000 km	Equatorial

Low Lunar Orbit (LLO): LLO is defined as a circular orbit of an altitude around 100 km. LLOs are favorable for surface access and polar orbit inclinations offer global landing site access.

An Elliptical Lunar Orbit (ELO), such as the 100 x 10,000 km shown, trades insertion costs with transfer cost to lunar surface.

Prograde Circular Orbits (PCOs) are defined as circular orbits of various sizes that rotate in the prograde direction and are highly stable, requiring few to zero corrections to be maintained.

Frozen orbits are similar but need not be circular and have orbital parameters that oscillate around fixed values.

New Twists:

Frozen orbits include Lunar Resonance Orbits that work from at least four inclinations 27^{o}, 50^{o}, 76^{o}, and 86^{o} Spacecraft in these orbits can stay in lunar orbit indefinitely with little or no makeup propulsion.