End-to-End Frequency Agnostic Remote Power and Ancillary Services

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Presentation Outline

Today's Presentation

- The Problem Space
- Finding Nexus
- Traversing the technology development "Valley of Death"
- XISP-Inc Evolving TD^3 Mission Set
- Power and Ancillary Service Beaming Facts
- Power & Ancillary Services Beaming Hypotheses
- Framing the Problem Space
- Orchestrating and Optimizing the Solution Space
- Applications & Customers
- 1^{st}, 2^{nd}, and 3^{rd} Mission Phases
- Challenges of Space Solar Power and ancillary services Beaming
- Next Steps
- Conclusion / Lunar Power & Light Company
- Resources
- Q&A / Mission Development Backup

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.
- Power and ancillary services 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

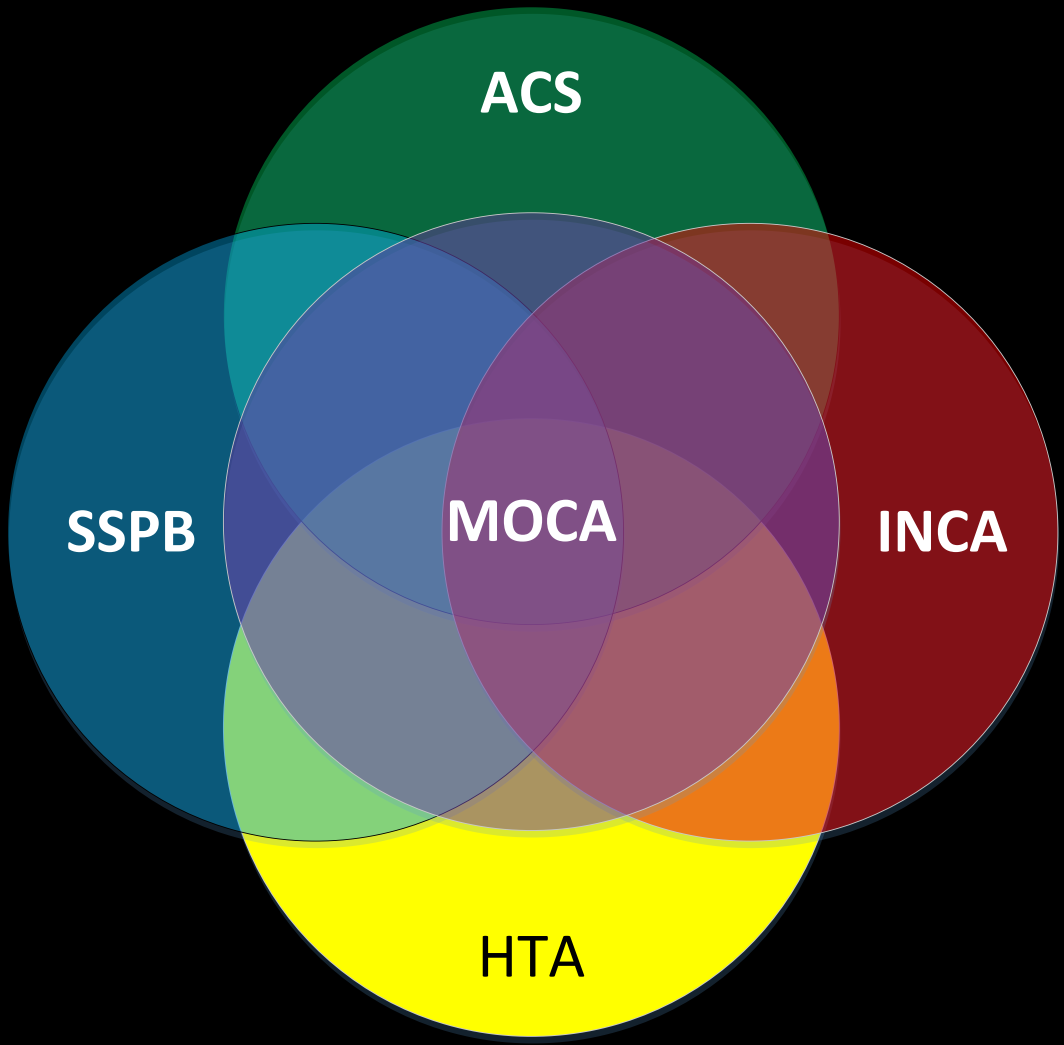
Alpha Cube Sat (ACS)

Space Solar Power and ancillary services Beaming (SSPB)

Mission Operations Control Applications (MOCA)

Interoperable Network Communications Architecture (INCA)

Halfway To Anywhere (HTA)



Power & Ancillary Services Beaming Facts

- Power and Ancillary Services Beaming is science fact not fiction; Dick Dickinson/JPL & Bill Brown/Raytheon set the world records circa 1975
  - ➔ maximum power 34 k DC over 1.6 km
  - ➔ end-to-end efficiency DC input to DC output power 54% over 1.7 m
- If you put enough energy in you can get what you need when and where you need it.
- The physics is frequency agnostic, but systems must be optimized to use.
- The efficient delivery of power and ancillary services is a complex systems engineering and economics problem.
- Power beaming is applicable to multiple venues (i.e., Space-to-space, surface-to-surface, Space-to-lunar/asteroid surface, Space-to-Earth)
- Power beaming services:
  - ➔ are no longer just in the lab, field demos in work across the globe
  - ➔ are scalable from less than a watt to gigawatts
  - ➔ require near real time link characterization
  - ➔ require ancillary services for control
  - ➔ need to meet actual customer requirements
  - ➔ need to make economic sense for the venue and application used
  - ➔ systems engineering needs to be reduced to practice

Power & Ancillary Services Beaming Hypothesis

Power and Ancillary Services Beaming can:

- Reduce/reallocate systems complexity, mass and/or volume
  - → "Plug in" and "Plug out" Technologies
- Provide for dispatchable energy transfer
  - → to alter the cadence of mission operations
- Reduce, eliminate, or deconflict power & ancillary services requirements
  - → energy generation, storage, distribution, and control
- Provide necessary ancillary services
  - → position/tracking, telemetry, commands, time, and payload data
- Better manage environmental interfaces
  - → dust, temperature, abrasive and irregular surfaces, etc.
- Enable more practical electro-mechanical interfaces
  - → robotic and EVA compatible
- Foster the identification and effective use of synergies
  - → power generation, storage, control, and distribution technologies
  - → Electrical and thermal control systems

Framing the Problem Space (1 of 3)

- Providing power and ancillary services (e.g., communications, command, control, telemetry, payload data transfer, time, navigation), when and where needed is essential to virtually all aspects of human endeavor and enables all forms of space exploration/development/settlement.
- Bootstrapping power and ancillary services entails that each increment of fielded must meet the needs of the present as well as serve as building blocks for the next increment.
- Construction of evolving increments must be an intrinsic part of the mission infrastructure.
- It is critical to determine what are the increments of scalable interoperable modular power and ancillary services needed to support:
  - LEO/MEO/GEO Operations
  - Cislunar logistics
  - Exploration Cislunar & Beyond
  - Settlement in the lunar environ
  - Ground & Space threat mitigation
  - lunar & asteroid prospecting
  - Space Manufacturing
  - Proving Reserves & Exploitation
  - Habitation
  - Orbital Debris mitigation

Framing the Problem Space (2 of 3)

- The current state-of-the-art with respect to providing viable power and ancillary services beaming to customers is effectively the null set.
- The necessary work to build viable end-to-end beaming systems is not new physics, rather it is a complex systems engineering & integration challenge and an economic one.
- While there are multiple terrestrial and even some space qualified technologies that could be leveraged to design viable end-to-end power generation, storage, and distribution systems suitable for multiple venues (Space-to-space, surface-to-surface, space-to-lunar/asteroidal surfaces, and Space-to-Earth the systems engineering of the same is nascent.

Framing the Problem Space (3 of 4)

- Accordingly, power and ancillary services beaming presents as an unresolved problem/solution space.
- This XISP-Inc mission development effort seeks to address this by generating, curating, intersecting, and converging multiple technology development efforts to yield a recommended set of deployable power and ancillary services beaming infrastructure payloads.

Orchestrating the Solution Space

- The solution space requires end-to-end systems otherwise you can not serve customers.
- The Technology Development, Demonstration, and Deployment (TD^3) work should be frequency agnostic since the physics does not change and the customer in most cases does not care.
- The work should retire/buy down both real and perceived risks associated with power and ancillary services beaming.
- The work should be scalable to at least the next increment.

Optimizing the Solution Space

- Systems-level power transfer efficiency can be calculated as a function of distance from the transmitter by starting with input power, the choice of transmit frequency band, the piecewise efficiencies of each element, and constraints due to the physics (or geophysics) of the natural environment.
- Electrical *and* thermal outputs can provide value in any context/venue, and can be orchestrated to maximize end-to-end systems efficiency for a wide range of supported applications - this is called “combined heat and power” in terrestrial power generation.

Applications & Customers

- Commercial space beaming applications include:
  - Expansion of operational mission capabilities,
  - Usable power per unit area needs to compare favorably with the Solar Constant (I_{sc}) and storage capabilities.
  - Multiplexed power and ancillary services (e.g., comm, command, control, telemetry, payload data, navigation, time → Situational Awareness).
  - Enhanced asset/infrastructure design flexibility, and
  - paving the way for the Lunar Power & Light Company.
- Government space applications include:
  - Sustainable, interoperable, scalable power generation, storage, and distribution.
  - Frequency agnostic extension of cognitive Software Defined Radios and Laser Communications.
  - Situational awareness.

1st Phase: Remote Services Demo

- Two 12U spacecraft buses with up to a square meter reflectarray optimizable photovoltaic array, integrated ancillary services Transmit and Receive apertures , and adaptive rectenna.
- Payload consists of a converged complement of microwave, millimeter wave, near infrared and optical transceivers; Viable Automated Space Tracking (VAST) sensors, data capture systems, and a near real-time state model to serve as a testbed for correlating predicted and measured performance.
- Integrated equipment sets based on defined hardware and software interfaces.
- Best of breed flat-sat terrestrial bake off tests of power beaming and the ability to interleave, modulate, or otherwise multiplex ancillary services

➔ proves useful power and ancillary services can be delivered to a customer, using modular, packageable and deployable components.

2^{nd} Phase: Remote Services Deployables

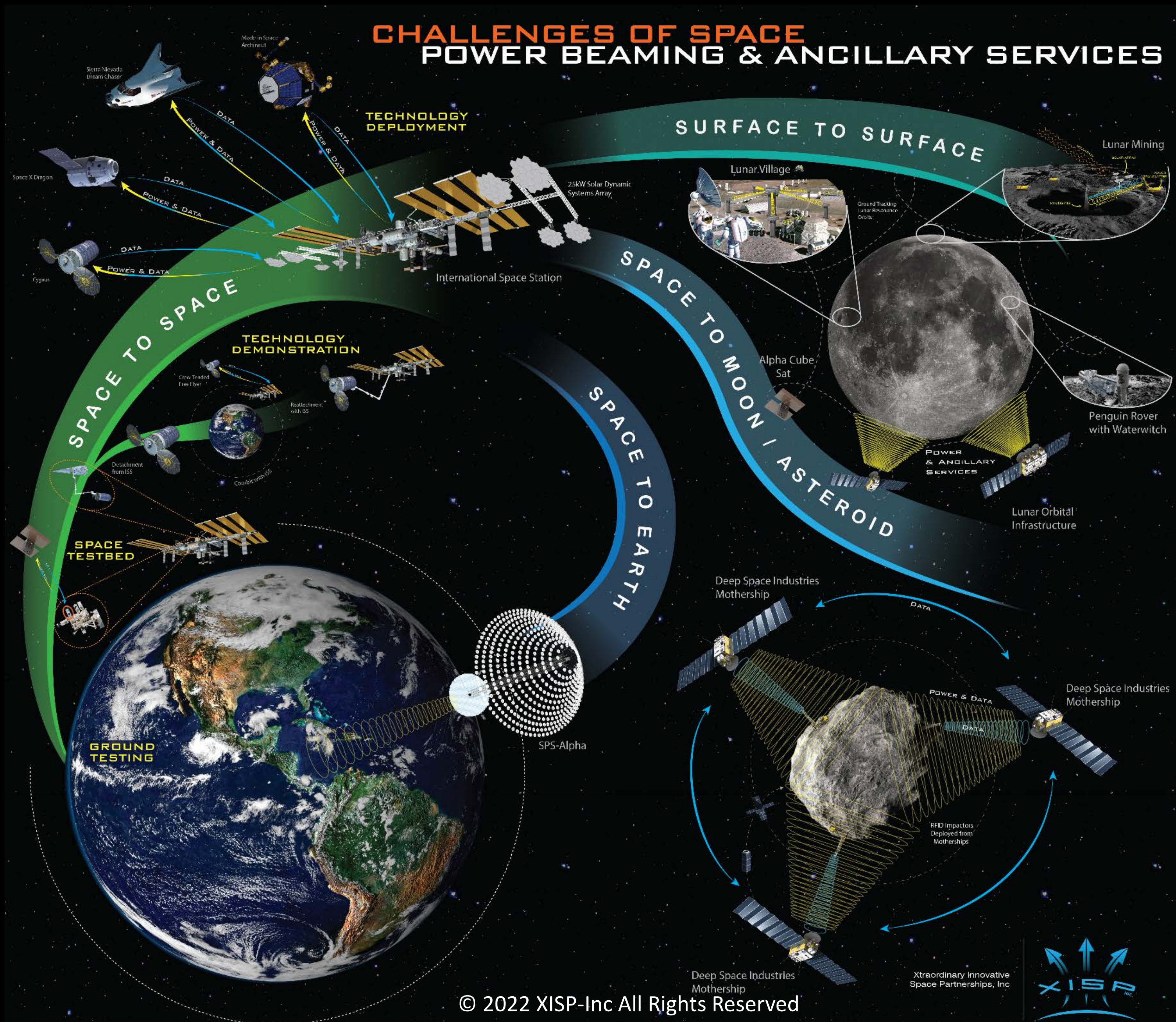
- Free-flyer Transceiver Platform: Up to 200 kg (ESPA ring scale) spacecraft with up to ten square meter reflectarray optimizable photovoltaic array, integrated ancillary services Transmit and Receive apertures , and adaptive rectenna.
- ISS mounted Transceiver: Up to 500 kg Dragon Trunk robotically compatible transceiver mountable on Bartolomeo/JEM Exposed Facility (up to 6 kW input power)
- Robotically Relocatable Transceivers: Suitable for accommodation on ISS Pressurized Logistics Carriers (e.g., Cygnus, Dragon) and Commercial Lunar Payload Services (CLPS) landers.
- Transceiver payloads consist of a repackageable complement of microwave, millimeter wave, near infrared and optical transceivers; optional one, two, and three axis gimbals; Viable Automated Space Tracking (VAST) sensors, data capture systems, and a near real-time state model for correlating predicted and measured performance.

➔ proves useful platforms can be fielded which provide power and ancillary services that can be optimized for delivery to some number of customers in some number of venues.

3rd Phase: ISS Remote Power & Ancillary Services Platform

- Using a combination of the refreshed Solar Arrays, an optional Solar Dynamic augment as originally specified, and potentially other generation and storage systems, a spacecraft with thousands of square meters of photovoltaic array (~2,500 m^2), integrated utility distribution, and locations for multiple transceivers and adaptive rectenna is potentially available.
- Using a combination of Cygnus/Dragon propulsion (near term) and an advanced water based propulsion testbed (longer term) which offer long duration low thrust, and short duration high thrust options, and low energy trajectory solutions the station altitude & orbital inclination can be altered.
- ***This would be a novel evolution for the ISS obviating the currently anticipated end of life at the bottom of the Pacific ocean.***
- Robotic and EVA compatible Technology Development, Demonstration, and Deployment (TD^3) payloads would consist of scalable modular elements to enable remote services support to a diaspora of commercial infrastructure.

➔ proves useful remote power and ancillary services can be delivered on reconfigurable platform that can scale as well as retiring perceived and real cost, schedule and technical risk reduction for large scale Space Solar Power infrastructure


CHALLENGES OF SPACE
POWER BEAMING & ANCILLARY SERVICES
TECHNOLOGY DEPLOYMENT
SURFACE TO SURFACE
Lunar Mining
Lunar Village
25kW Solar Dynamic Systems Array
International Space Station
DATA
POWER & DATA
SPACE TO SPACE
TECHNOLOGY DEMONSTRATION
SPACE TO MOON / ASTEROID
Alpha Cube Sat
Penguin Rover with Waterwitch
POWER & ANCILLARY SERVICES
Lunar Orbital Infrastructure
SPACE TO EARTH
SPACE TESTBED
GROUND TESTING
SPS-Alpha
Deep Space Industries Mothership
Deep Space Industries Mothership
Deep Space Industries Mothership
Xtraordinary Innovative Space Partnerships, Inc
XISP

The Fine Print

- XISP-inc is building a mission development consortium to make this work.
- Consortium participants at various levels include XISP-Inc, Raytheon Technologies, multiple consultants, potential commercial component suppliers, university space systems labs, government agencies, non-profit organizations, and other national space agencies/contractors.
- The XISP-Inc Power & Ancillary Services Beaming mission has standing with the NASA Space Operations Mission Directorate (SOMD) Space Communications and Navigation (SCaN) Program Office as a commercial Technology Development, Demonstration, and Deployment (TD^3) mission but has received no direct government funding to date.
- XISP-Inc successfully negotiated an Unfunded Space Act Umbrella Agreement for TD^3 mission development with the NASA Human Exploration and Operations Mission Directorate and is seeking similar funded or unfunded authority under SOMD.

➔ ***XISP-Inc has invested in cash and in-kind approximately $3 Million dollars into related TD^3 mission development efforts over the last decade. Other consortium participants have been self-funded and are not included in this total.***

Next Steps

- ISS can be an asset for early Technology Development of SSPB
- Lunar Surface Innovation Consortium (LSIC) developed requirements need to be infused into both the NASA program plans and the orchestrated international lunar campaigns.
- Provide early and frequent opportunities for protoflight experiments on CLPS and HLS.
- Leverage the synergies between EMD, OMD, SMD, and STMD to realize fielded test bed systems at the earliest opportunities.

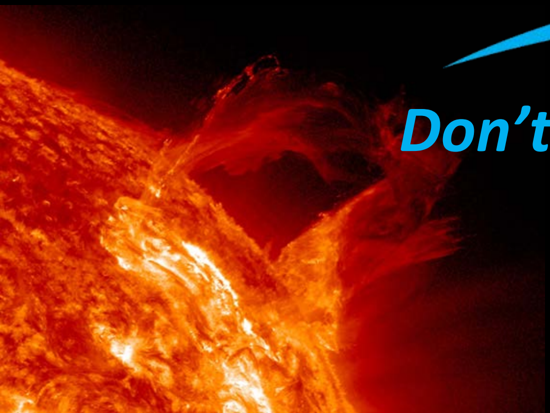
Conclusion

- Space Solar Power and ancillary services Beaming (SSPB) has transitioned from a conceptual mission ripe with opportunity to multiple missions with recognized standing across multiple NASA mission directorates and international partners.
- A confluence of interests biased toward successful execution of the mission as Public Private Partnership can be defined.
- Successful demonstration of SSPB will:
  1. Reduce the perceived cost, schedule, technical risk of Space Solar Power systems,
  2. Pave the way for Space Solar Power 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 build it!

Lunar Power & Light Company

an XISP-Inc Consortium



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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

Q&A/Mission Development Backup

Q&A Mission Development Backup Outline

- Critical Considerations
- Key Variables
- Challenge Matrix
- Available Data Sets
- Sustainable Power Generation, Storage, and Distribution Block Diagrams
- Trade Space Methodology
- Power Density vs. Solar Constant (I_{sc})
- Calculating Efficiencies
- Cubesats are a viable Technology Development Platform
- ISS is a resource for Early Technology Development
- Accommodation Requirements
- Surface-to-Surface Space Solar Power and ancillary services Beaming (SSPB)
- Beam Component Enabling Physics
- Beam Component Uses
- Beaming Technological Challenges
- Interoperable Network Communication Architectures
- Non-technical Challenges & Opportunities

Critical Considerations

- 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 (Continued)

- 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

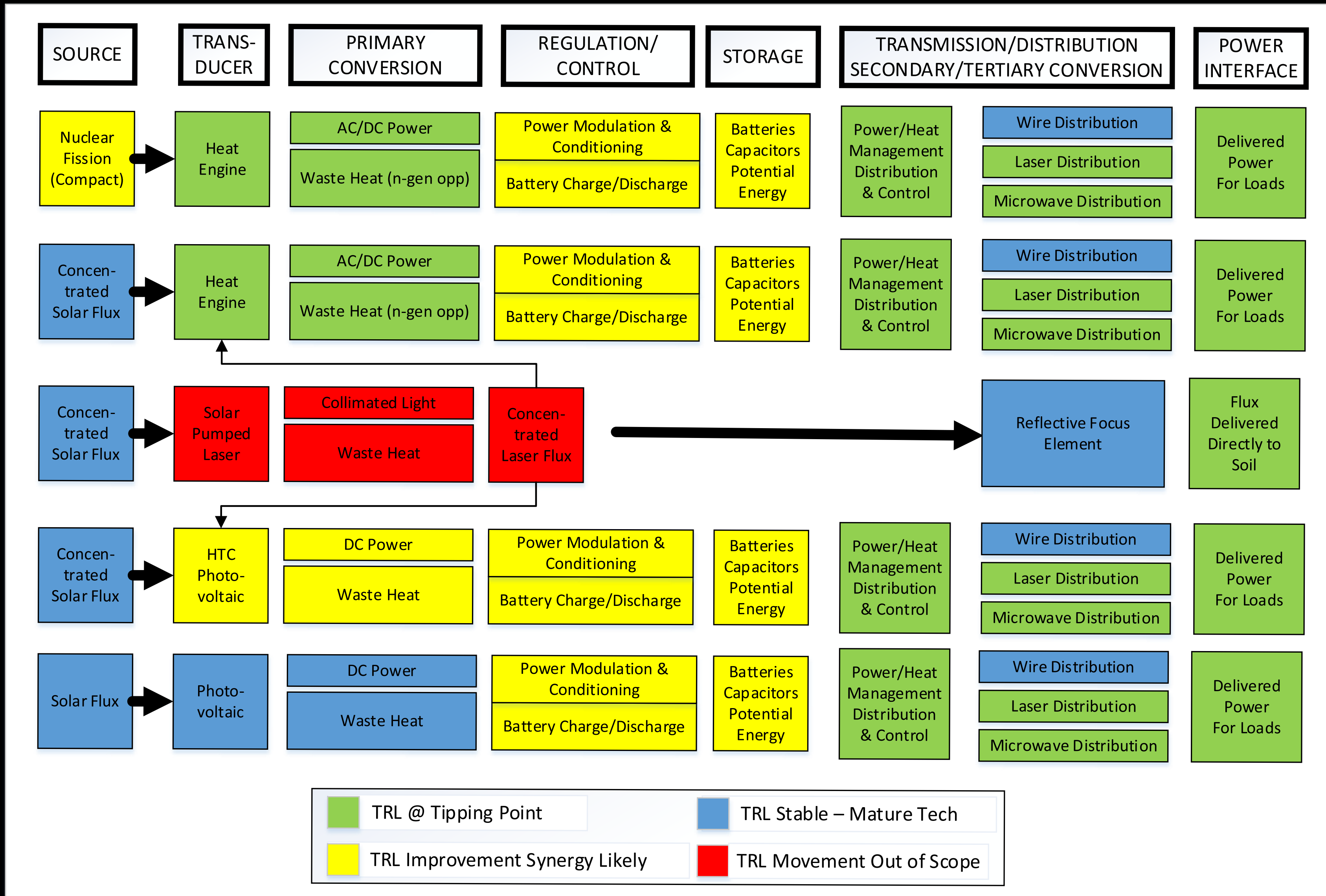
Relative Value of Delivered Power

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

Available Data Sets

- The first data set is the Vendor User's Guides for the NASA Commercial Lunar Payload Services (CLPS) contract lunar lander and the Human Lander Services (HLS) spacecraft/payloads.
- The second data set is the customer requirements of prospective payloads which are broken into four increments:
  - 1 kW: initial exploration
  - 10 kW: prospecting
  - 100 kW: quantifying/proving reserves
  - 1,000 kW: exploitation, habitation, and settlement.
- The third data set is the accumulated theoretical/experimental test data for:
  - transmitter options,
  - rectenna/receiver options, and
  - end-to-end efficiency for microwave, millimeter wave, and infrared/optical frequencies.

Sustainable Power Generation, Storage, and Distribution



Trade Space: Interface Planes

Voltage/ Amp Regulation (Input Power)

Batteries Capacitors Potential Energy

Storage Charge/ Discharge Mgmt.

External Interfaces . . .

Transmission/Distribution & Secondary/Tertiary Conversion

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

Optical & Millimeter wave 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

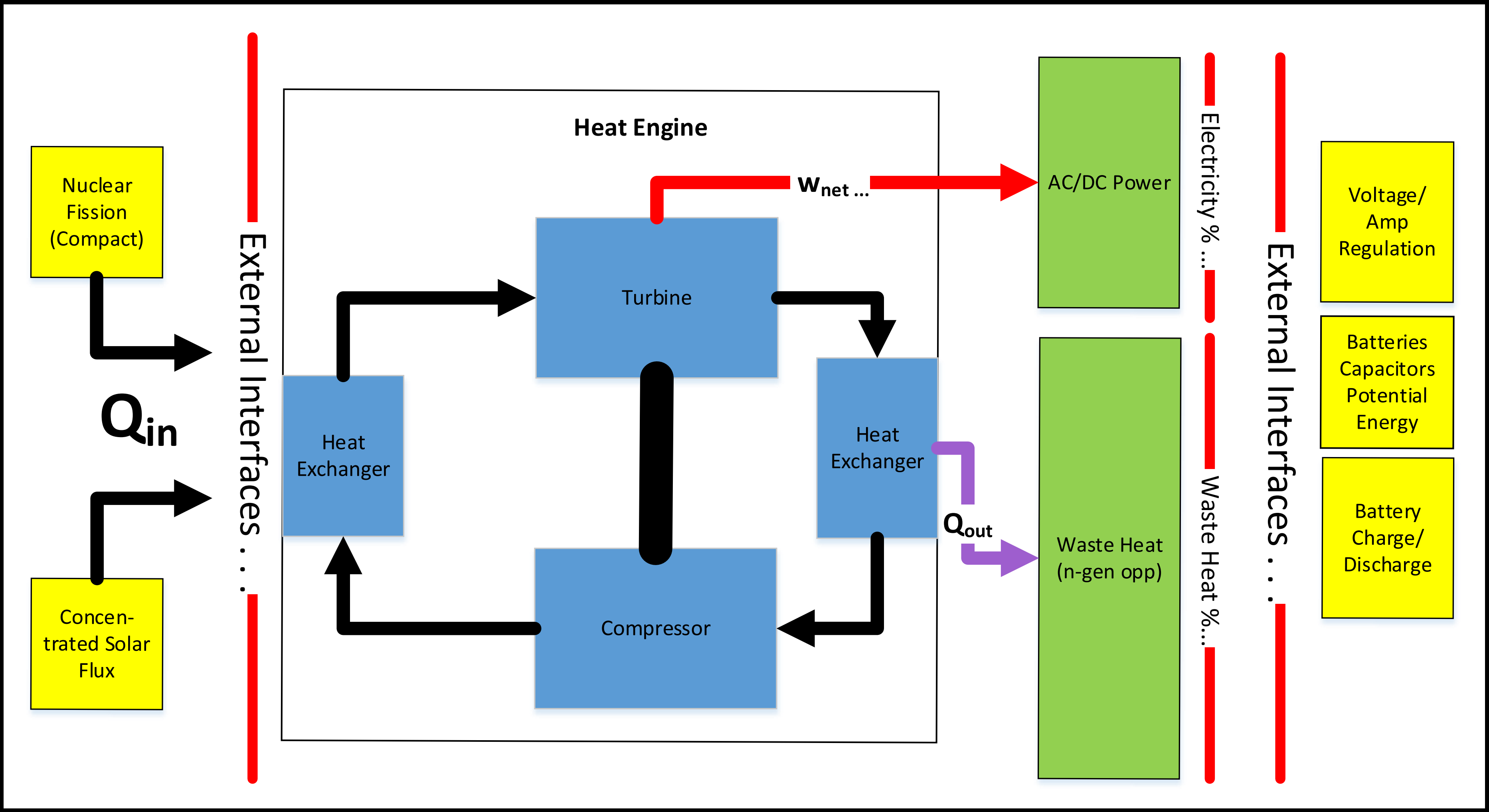
- Instrumentation (e.g., Sensors, Gauges, and Actuators)
- Data Handling, Storage, and Processing
- State Model
- Control Logic
- Management Operations Control Applications (MOCA)

External Interfaces . . .

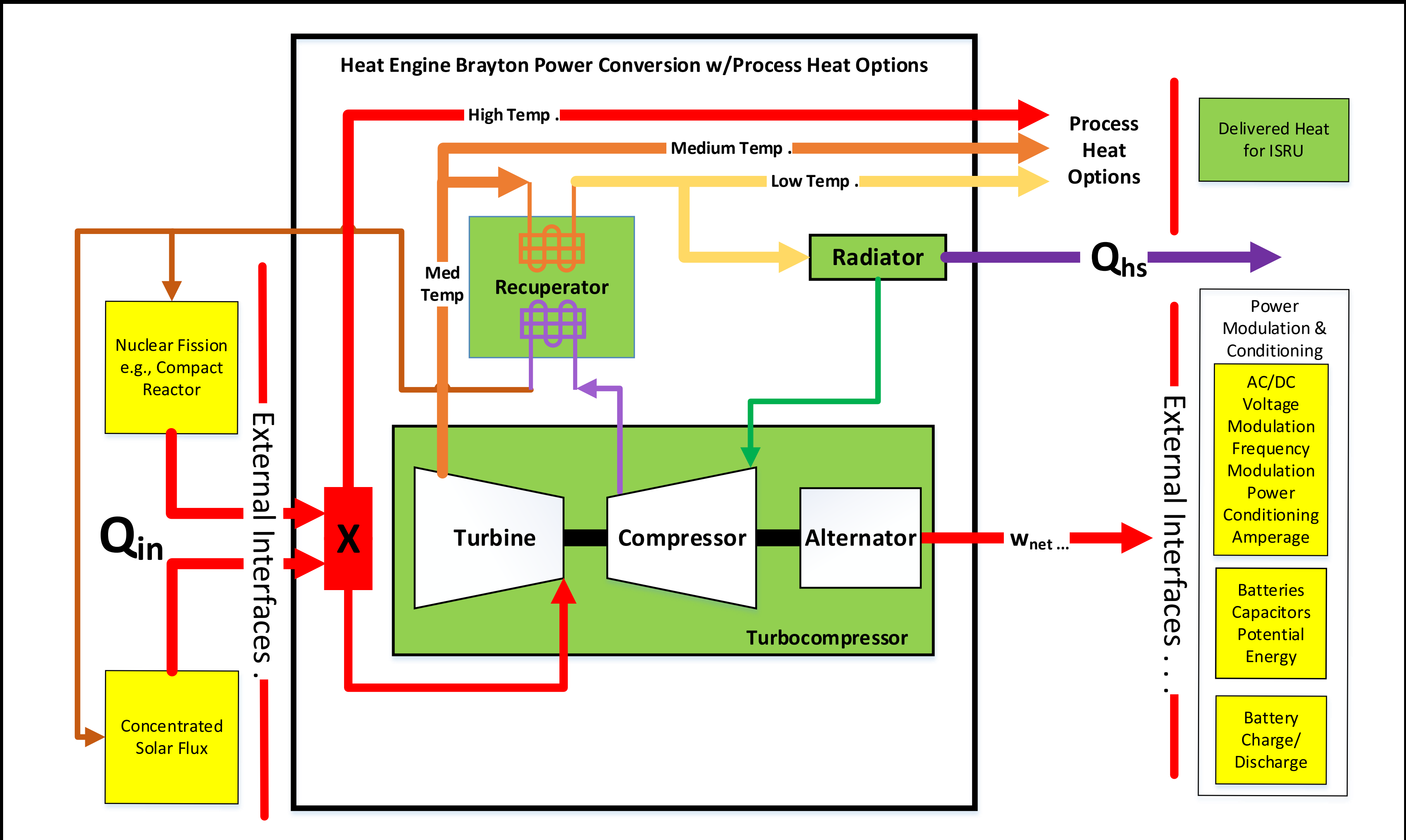
Delivered Power For Loads

TRL @ Tipping Point	TRL Stable – Mature Tech
TRL Improvement Synergy Likely	TRL Movement Out of Scope

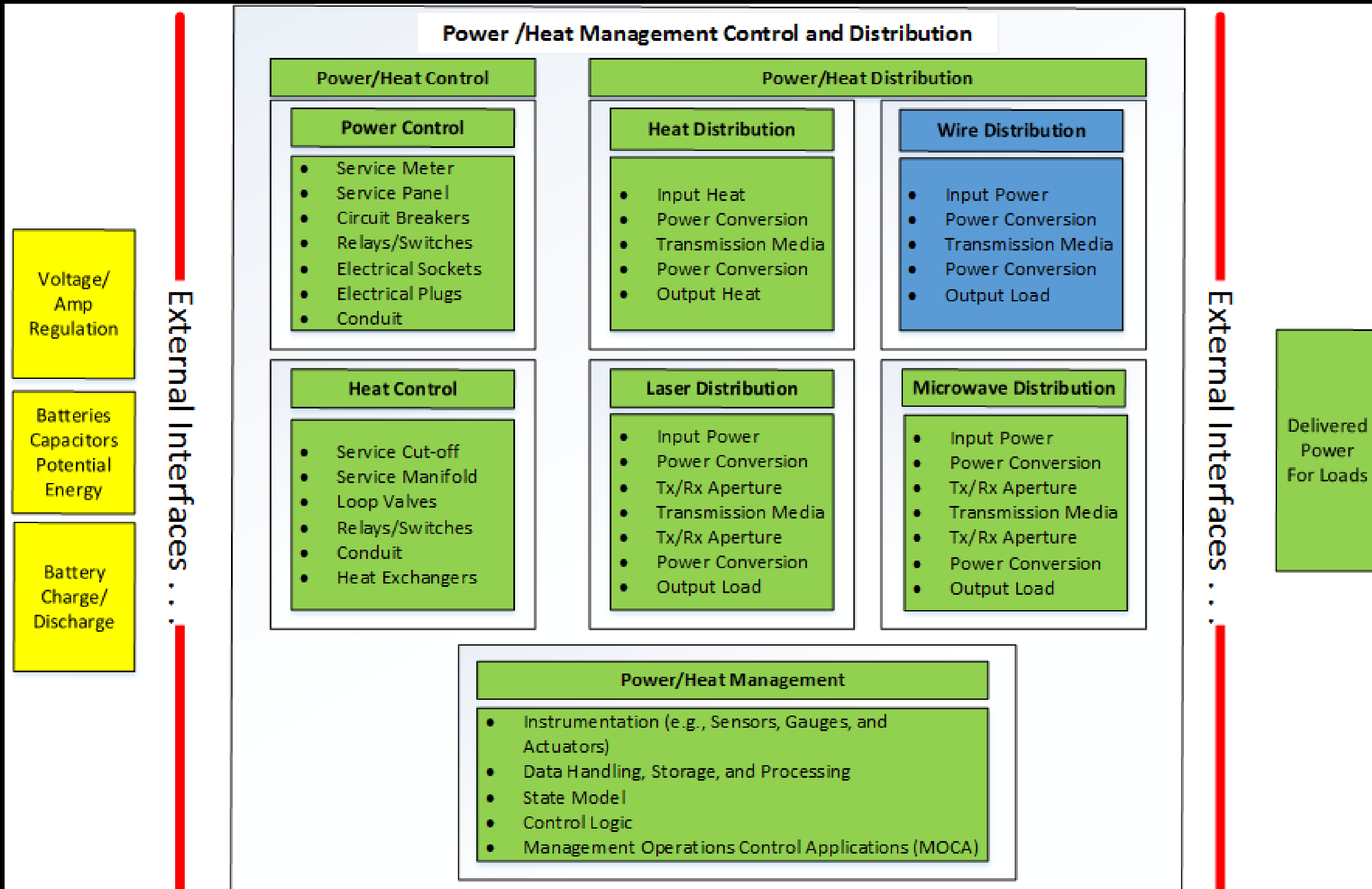
Flows Across Interfaces are a Design Driver



Applied Engineering Extensible to Other Systems/Subsystems



Power Distribution



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*.

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} (pink)
	P_d similar to I_{sc} (yellow)
	P_d significantly higher than I_{sc} (green)

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

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/Millimeter Theoretical & Experimental Efficiency

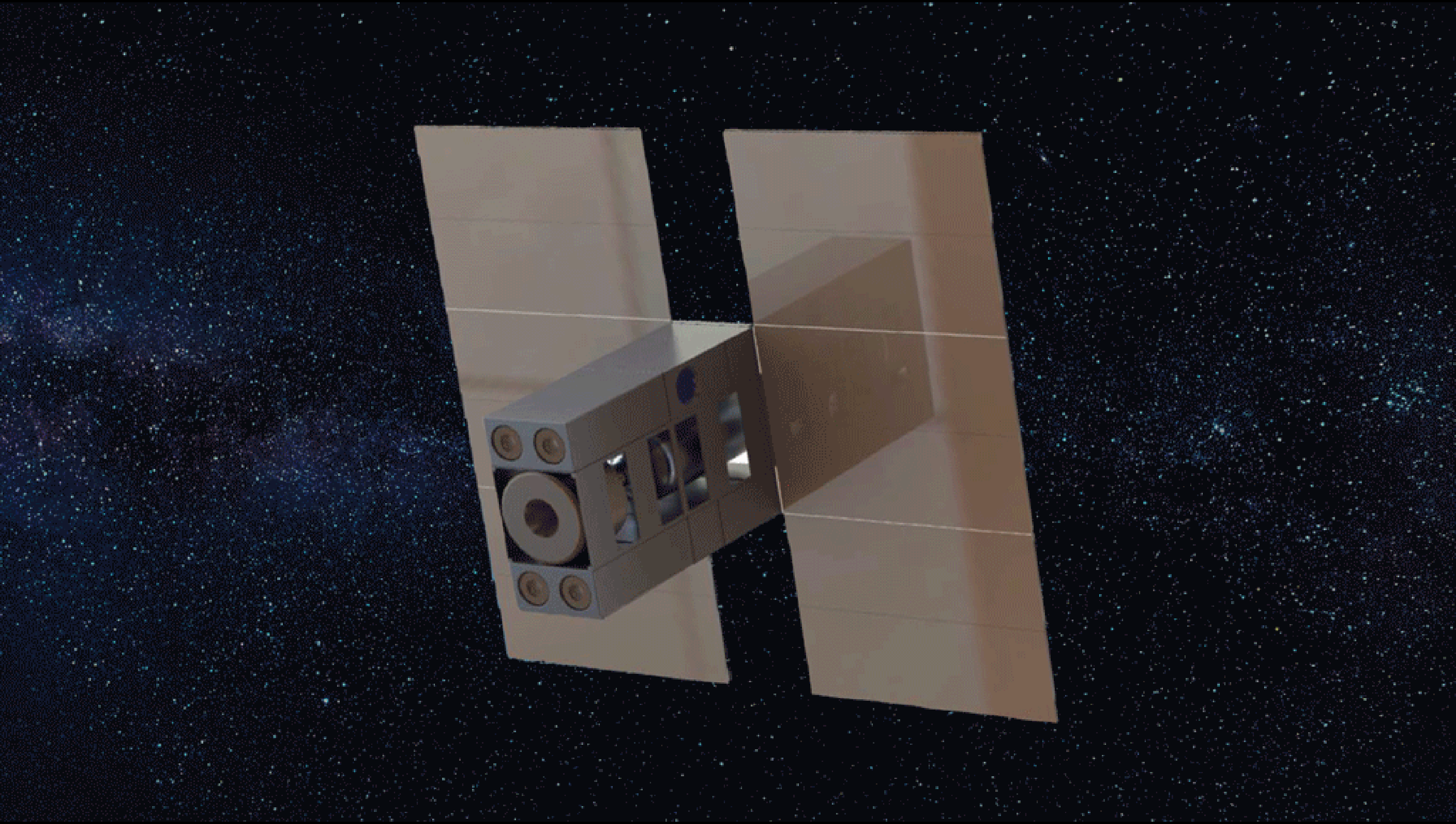
Published Year	Input Power (W)	DC to MW Conversion Efficiency	Beam Forming Antenna Efficiency	Free Space Transmission Efficiency	MV to DC Conversion Efficiency	Output Power (W)	DC -to-DC Projected Efficiency	DC -to-DC Demonstrated Efficiency	DC -to-DC Theoretical Efficiency	Beam Frequency	Data Source
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%	Used 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%	Used 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%	Used 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 Target**	**95%**	**Frequency Agnostic (but not Atheist)**	**XISP-Inc, aspirational**

NOTES:

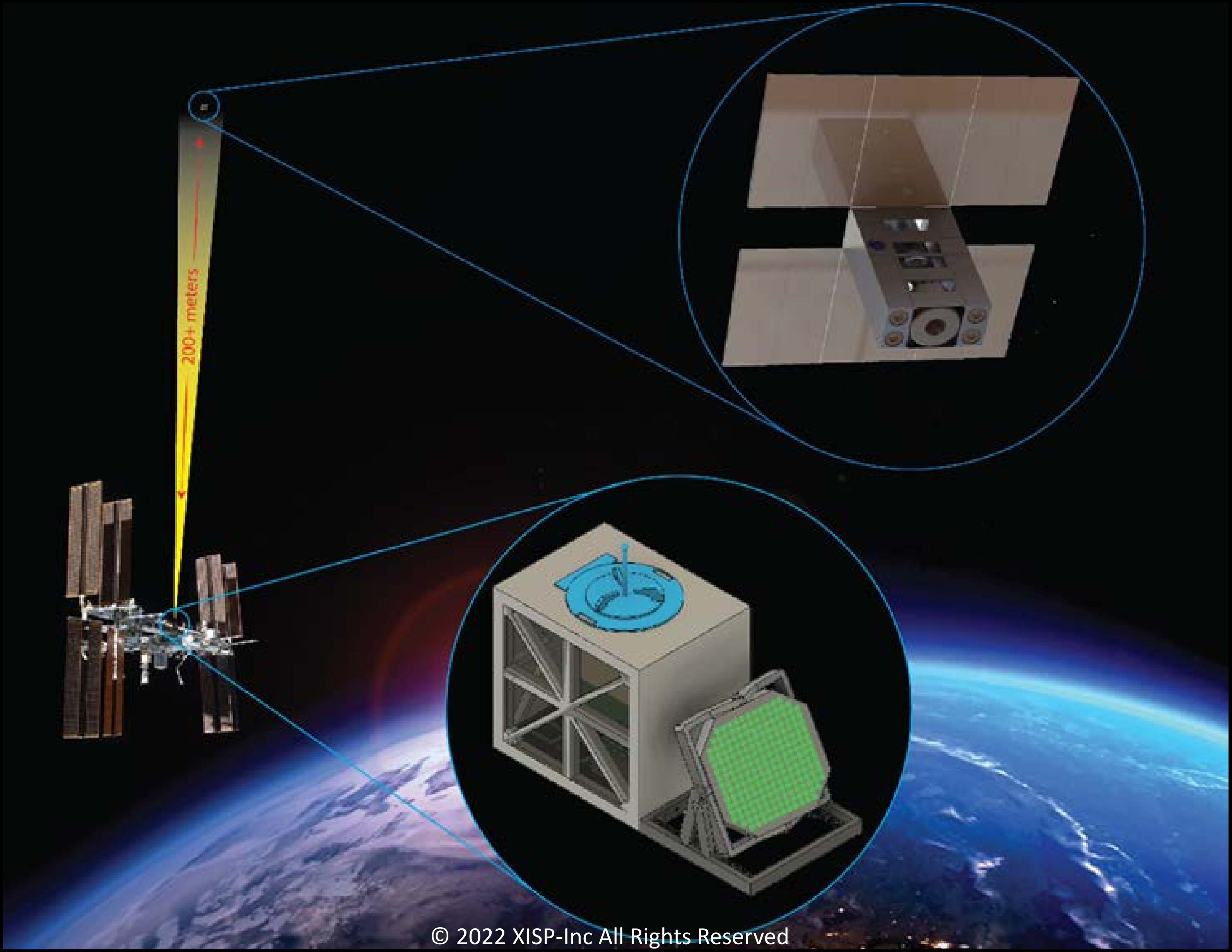
1	William C. Brown, Life Fellow, IEEE, and E. Eugene Eves, Beamed Microwave Power Transmission and its Application to Space, IEEE Transactions On Microwave Theory and Techniques, Vol. Ro, No. 6. June 1992
2	Gary P. Barnhard, Daniel Faber, Space-to-Space Power Beaming - An Evolving Commercial Mission 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

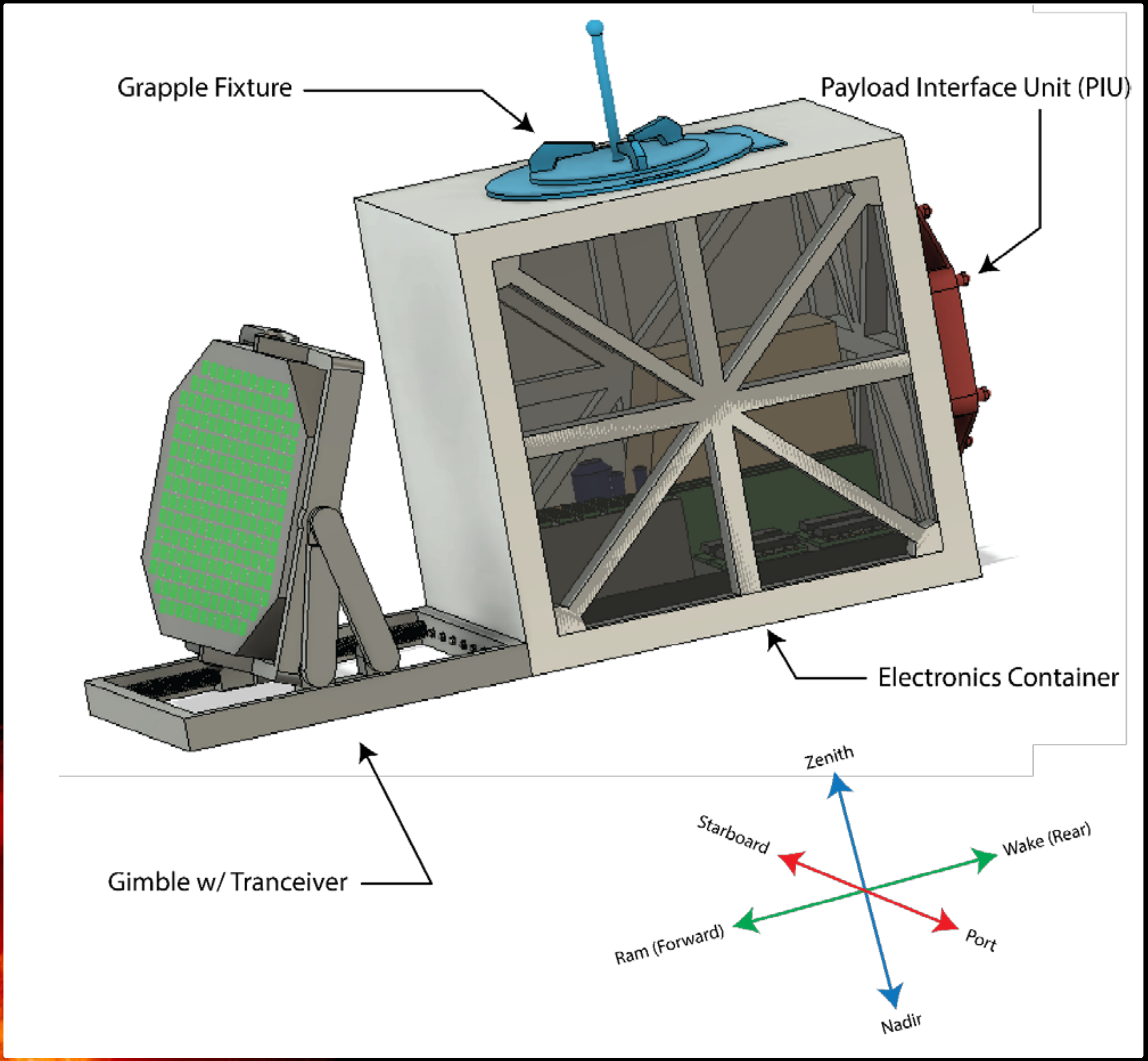
CubeSats are Viable Tech Dev Platforms



ISS is a Resource for Early Tech Dev



ISS SSPB Transceiver Preliminary Design Isometric



Advanced Converged Reflectarray Concept

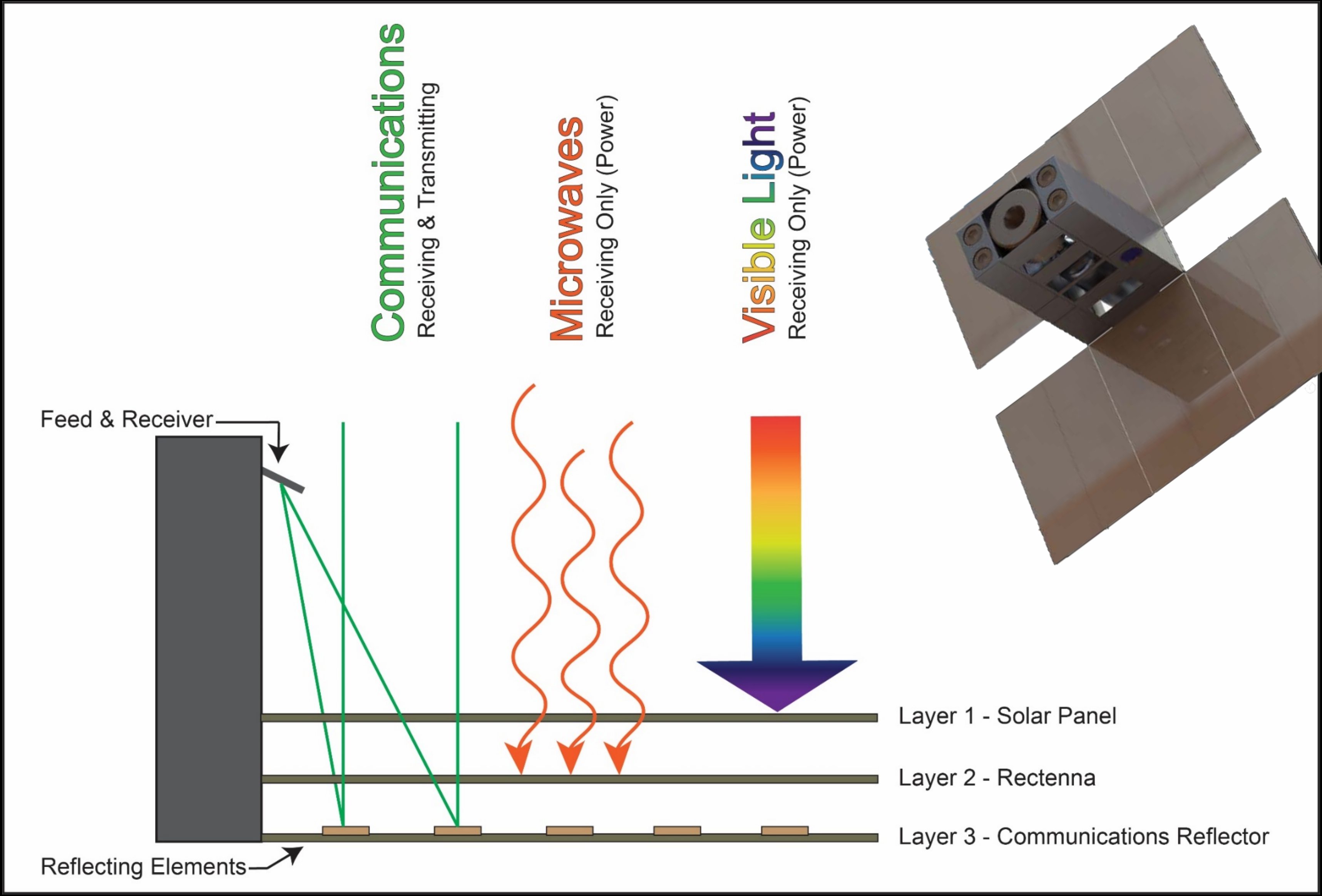
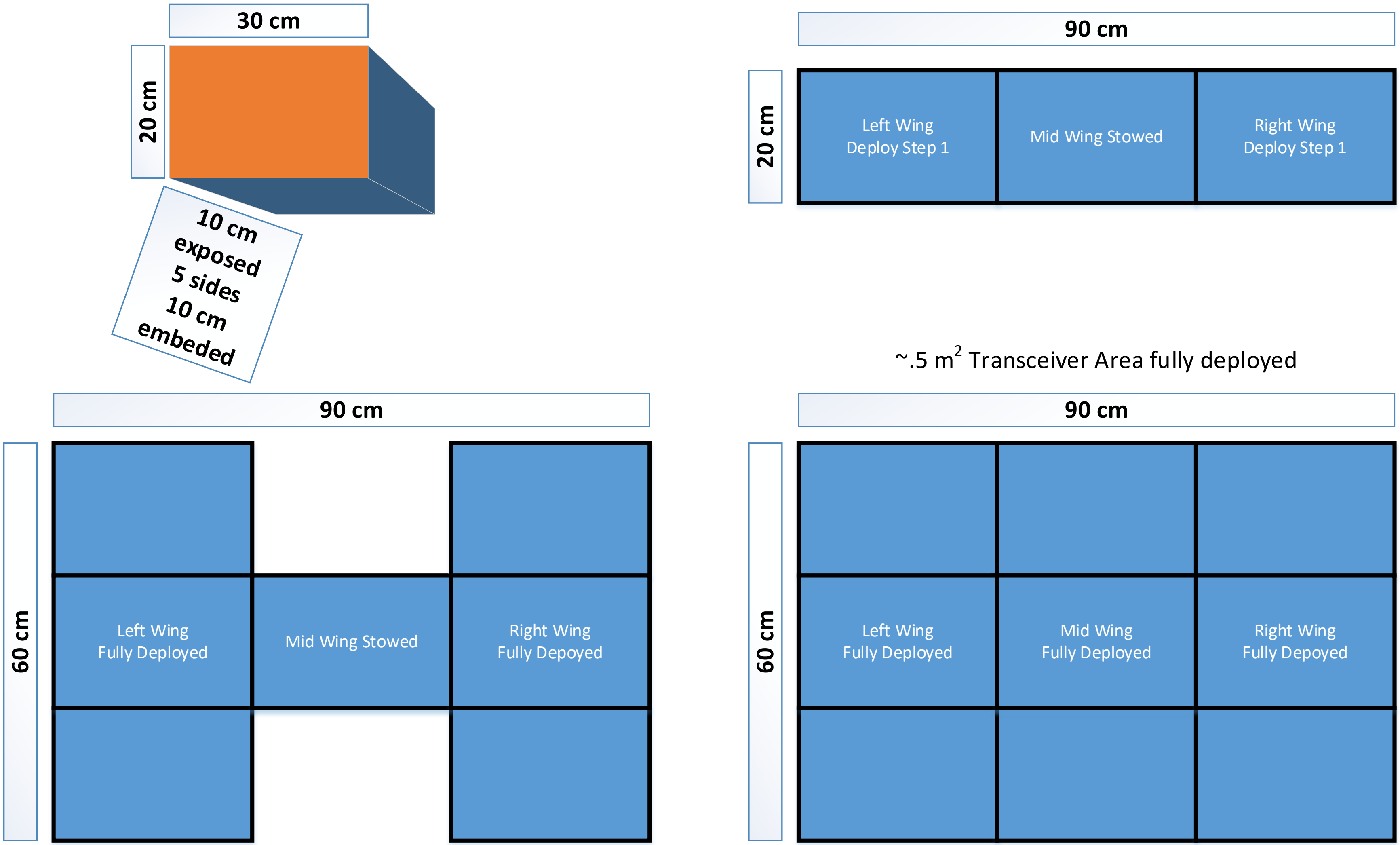
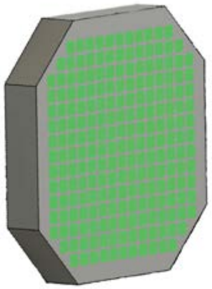
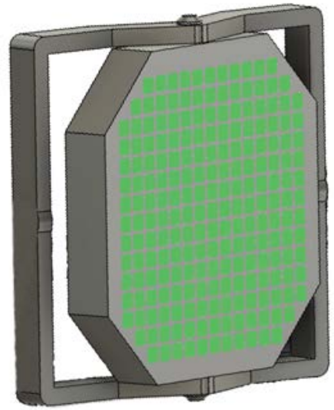


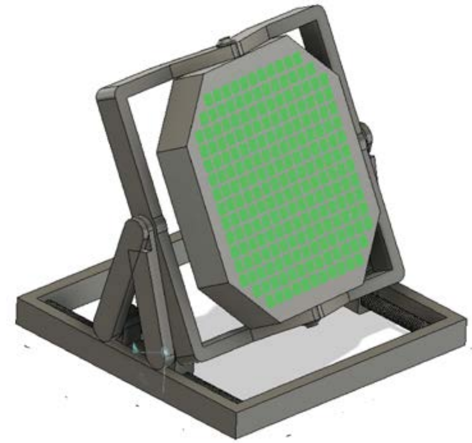
Figure 3 – Conceptual Fold-Out Array from a partially embedded 12 U cubesat scale payload*

* ~12 U Payload Stowed is an aspirational volume until repacking of the control electronics and thermal management requirements are addressed)









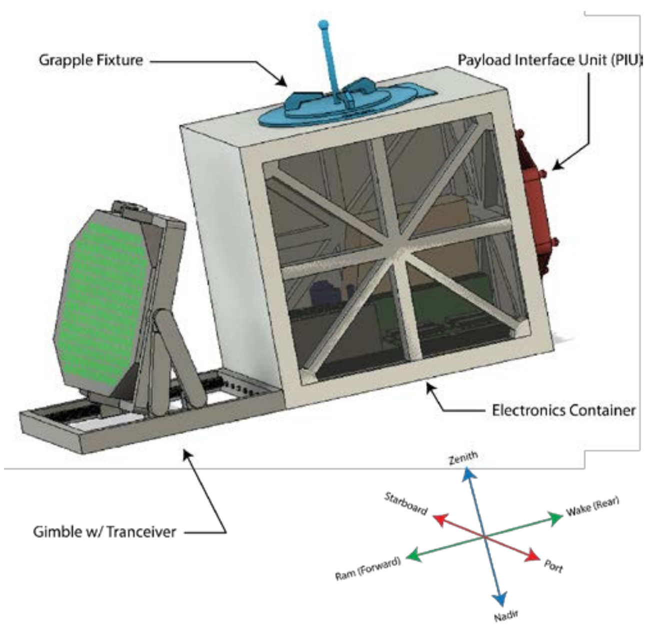
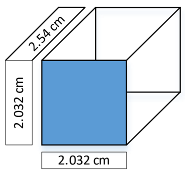
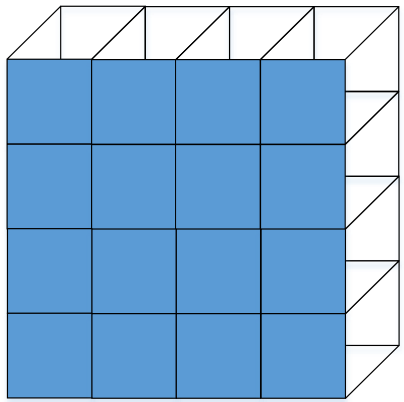

Grapple Fixture
Payload Interface Unit (PIU
Electronics Container
Gimble w/ Tranceiver
Zenith
Starboard
Wake (Rear)
Ram (Forward)
Port
Nadir

Figure 5 – Scalable Transmitter Design .1 kW to 10 kW Deployable Payload Service Package

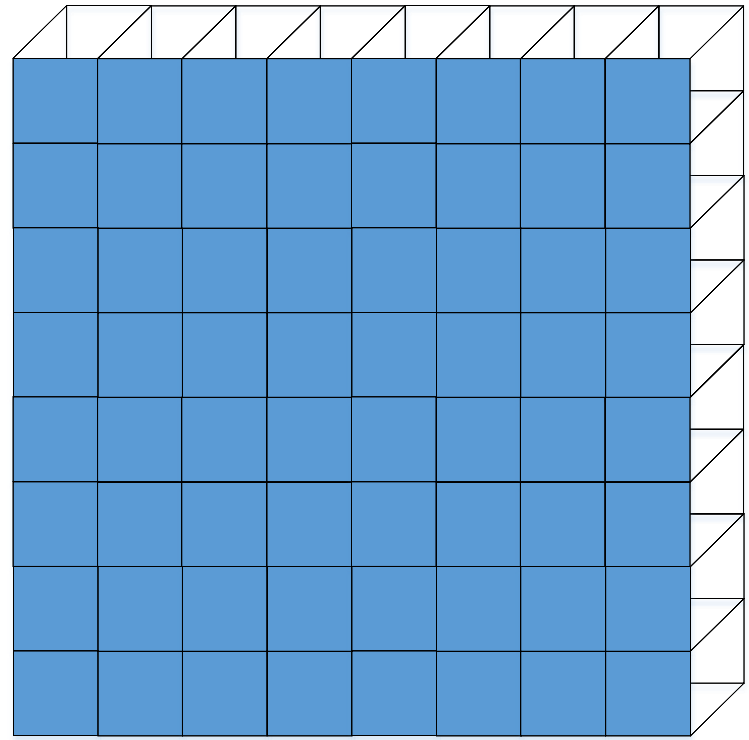
*Based on Raytheon Monolithic Microwave Integrated Circuit (MMIC) Power Amplifier (PA) Submodule, Module, and Array Assemblies which have been developed and demonstrated**



Submodule Assembly
7 W+ Radiated Power
@~95 GHz
(2 Driver MMICs & 8 PA MMICs)



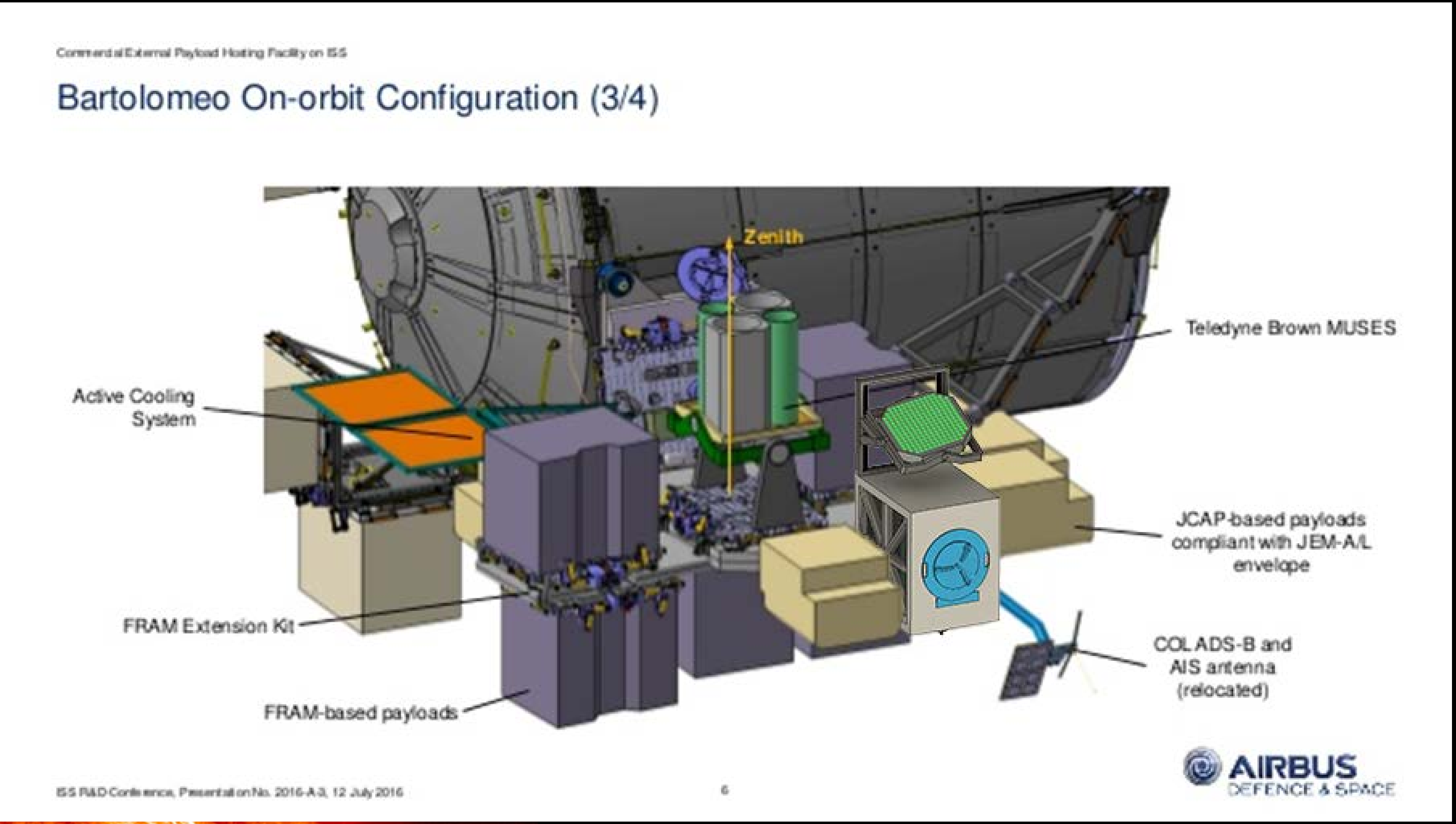
Module Assembly
8.128 cm X 8.128 cm (<.1 m^2)
100 W+ Radiated Power
@~95 GHz
(16 Submodules)



Array Assembly
65.024 cm x 65.024 cm (<.5 m^2)
7 kW Radiated Power
@~95 GHz
(8x8 Array of 100 W+ modules)

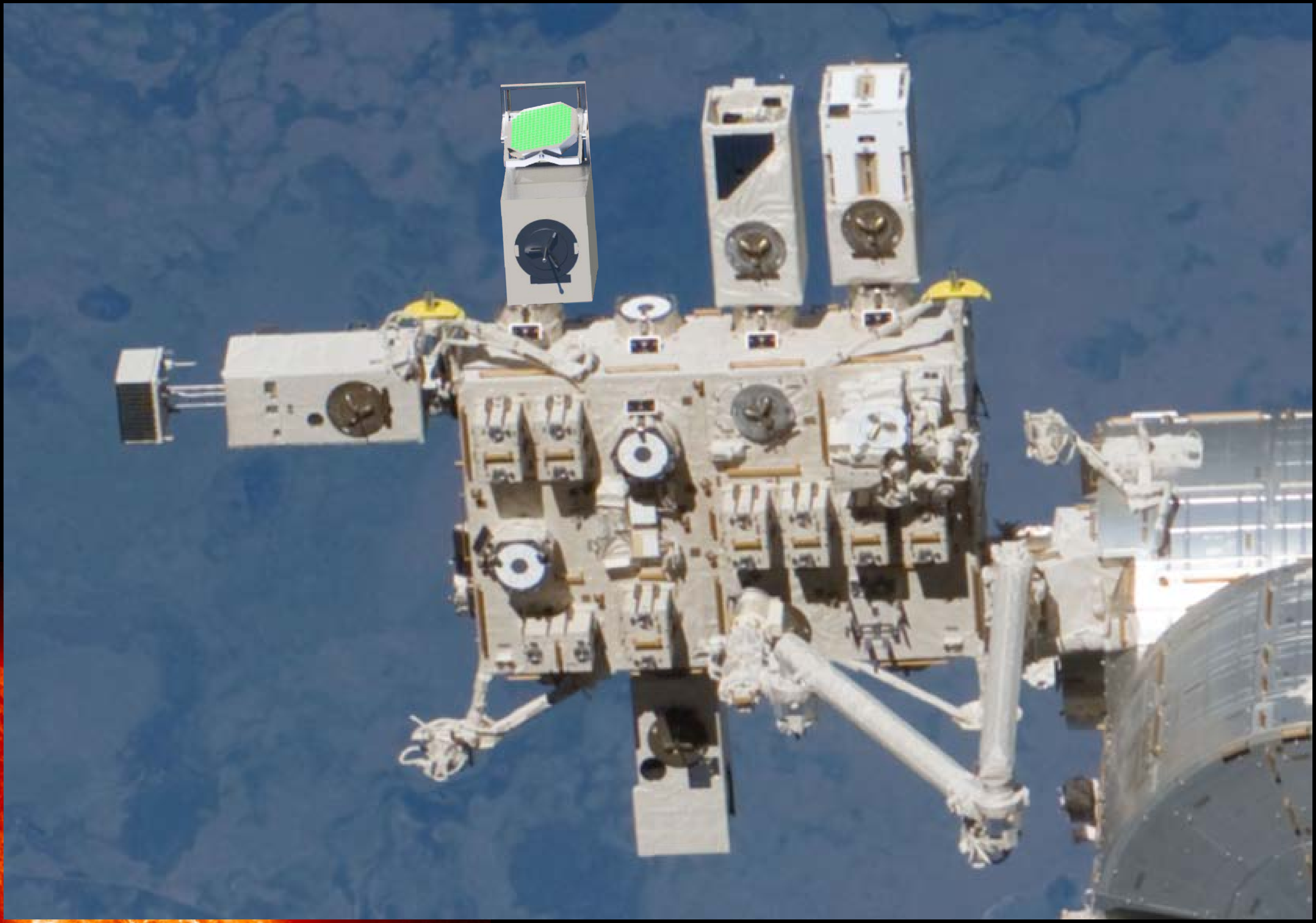
7kW GaN W-Band Transmitter
Ken Brown, Andrew Brown, Travis Feenstra, Darin Gritters, Shane O'Connor, Mike Sotelo, Raytheon, RMS; Nick Kolias, K. C. Hwang, Jeffrey Kotce, Raytheon IDS; Ed Robinson, U.S. Army ARDEC -- IEEE 2016*

Barto Exposed Facility Accommodations



Art Work Credit: XISP-Inc derived from AIRBUS

JEM Exposed Facility Accommodations



Art Work Credit: XISP-Inc derived from JAXA

Robotically Compatible Cygnus & Dragon Free flyers Accommodations

THE VALUE OF PERFORMANCE.
NORTHROP GRUMMAN

SPACEX

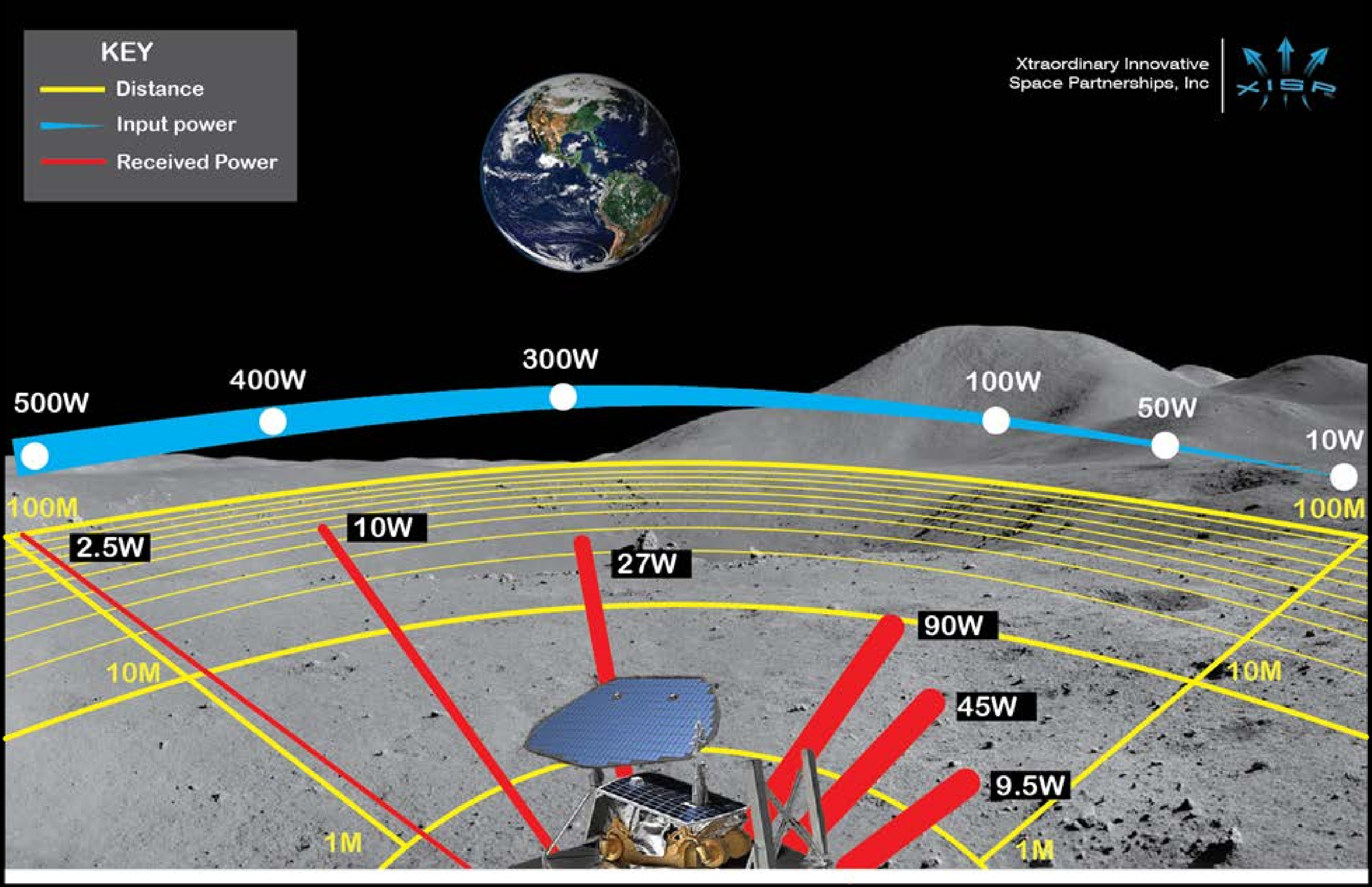
Art Work Credit: Northrop Grumman & SpaceX

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 -- Power connection interface
  - -- Data connection interface --Thermal management interface
  - -- Launch environment -- Landing environment
  - -- Operating environment -- Quiescent/keep-alive environment
- What are the safety, quality assurance, and quality control considerations?

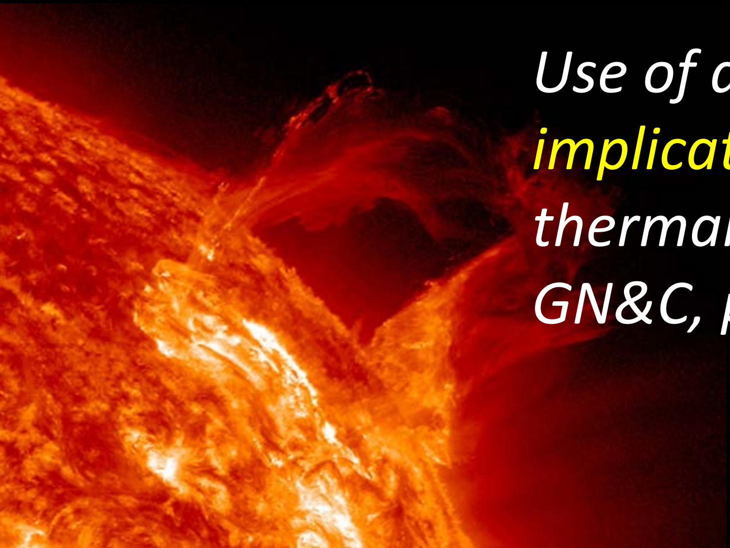
Surface-to-Surface Power Beaming

CLPS 15 Kg Power Beaming Testbed
XISP-Inc/Raytheon Proposal submitted for SMD LSITP 2019



Beam Component Enabling Physics

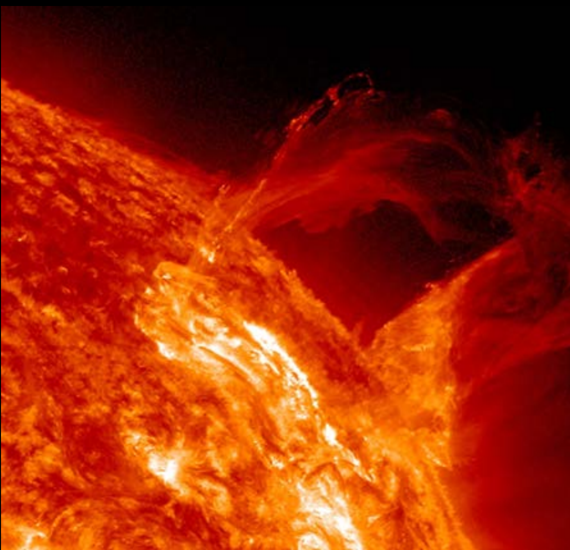
- Radiant energy beam components include:
  - Electrical,
  - Magnetic,
  - Linear & Angular Momentum,
  - Thermal, and
  - Data.
- There are potential direct and indirect uses for each beam component.



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

Beam Components: Uses

- In theory, the use of the beam 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



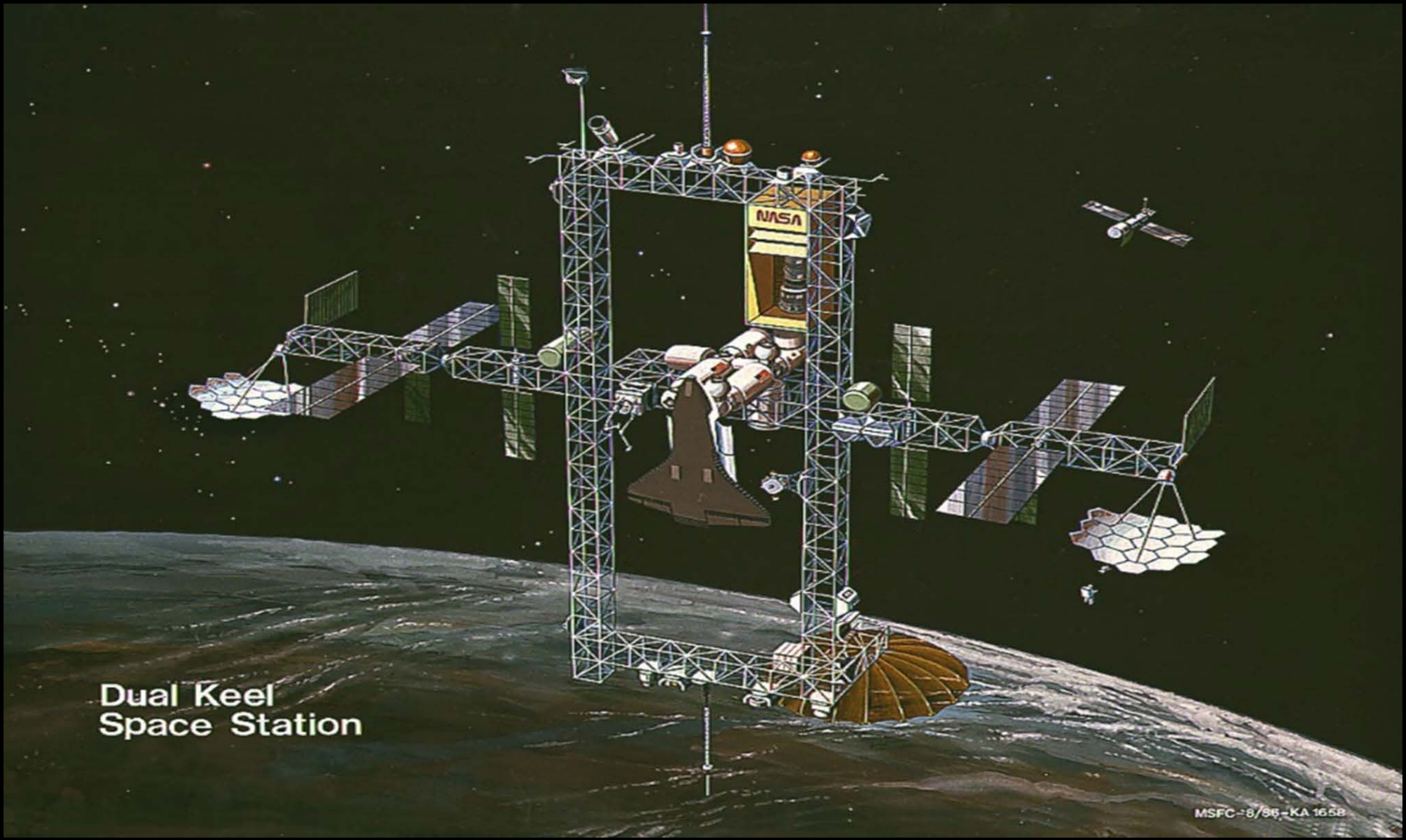
In theory, there is no difference between theory and practice – but in practice, there is.
– Jan L.A. van de Snepscheut
computer scientist

Technological Challenges

- The physics of near field/far field energy propagation is well understood.
- The uses of radiant energy to transfer: power, data, force, &/or heat, either directly and/or by inducing near field effects at a distance, is not sufficiently characterized.
- There is a very limited engineering knowledge base of practical applications.
- This is applied engineering work, (a.k.a. technology development), not new physics.

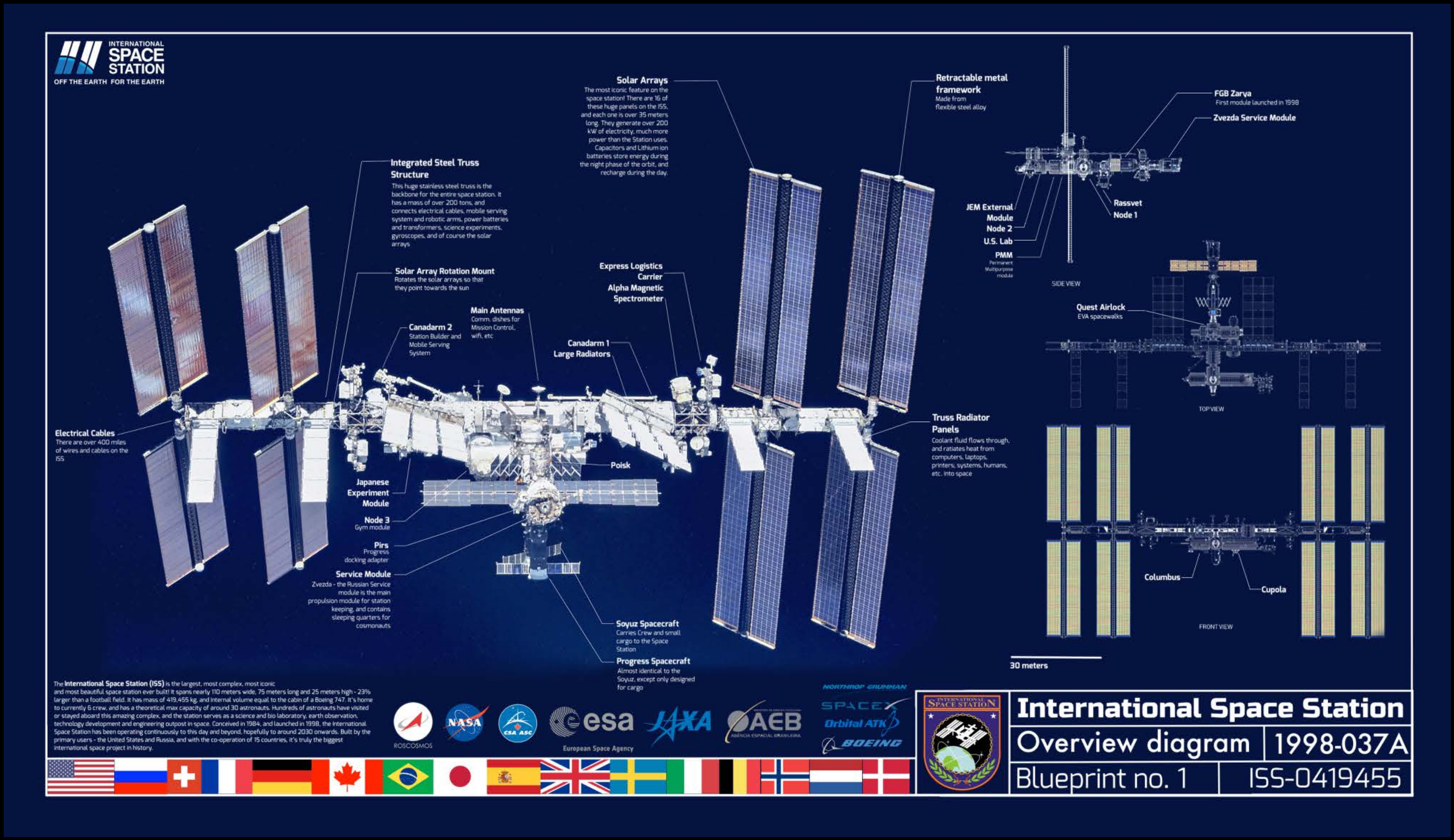
To optimize beaming applications we need to better understand how each of the components of radiant energy can be made to interact in a controlled manner.

Early Space Station Design w/Solar Dynamic



Art Work Credit: NASA

International Space Station Design

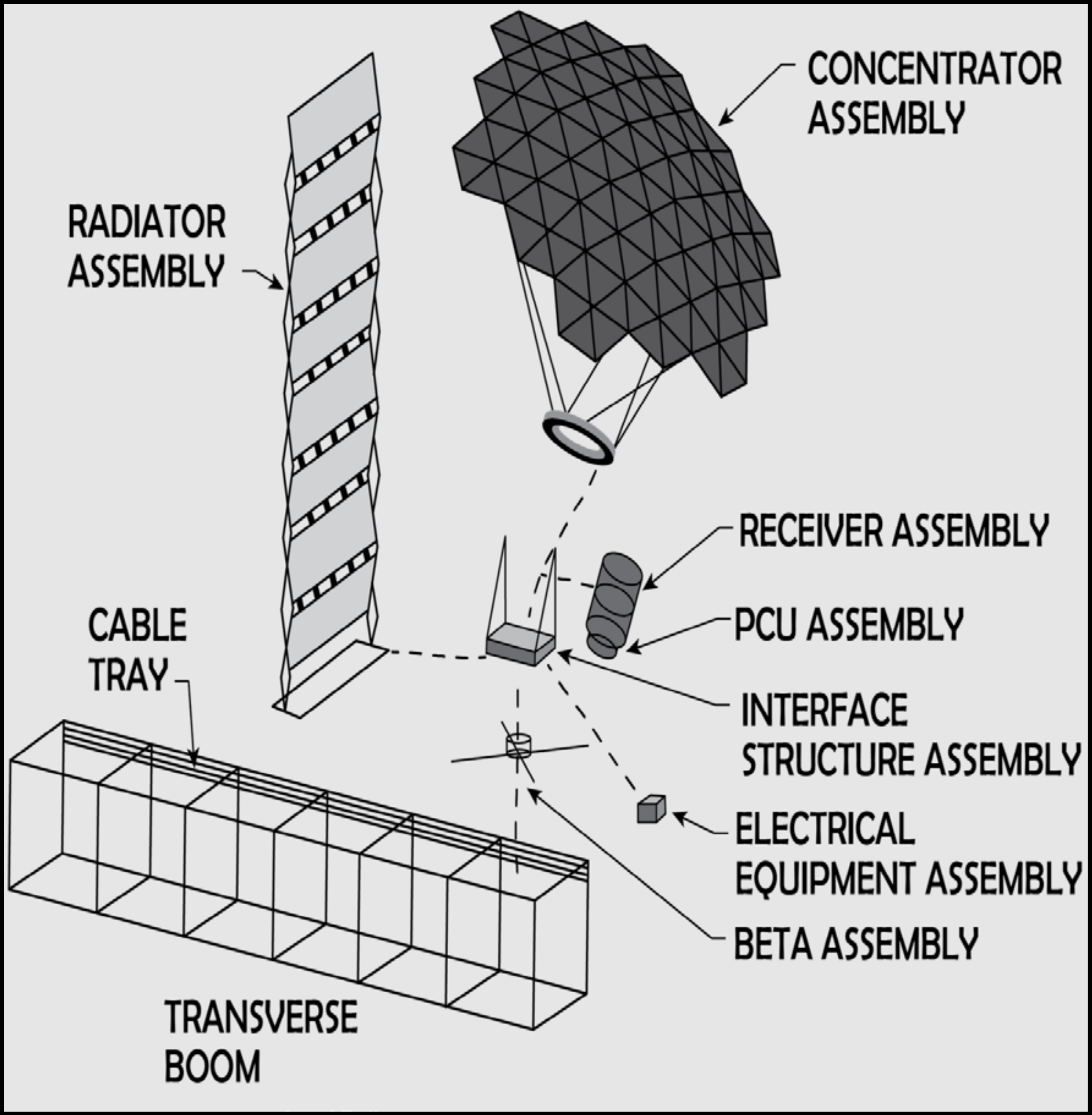


Art Work Credit: NASA

LaRC/GRC 2kW Solar Dynamic Test

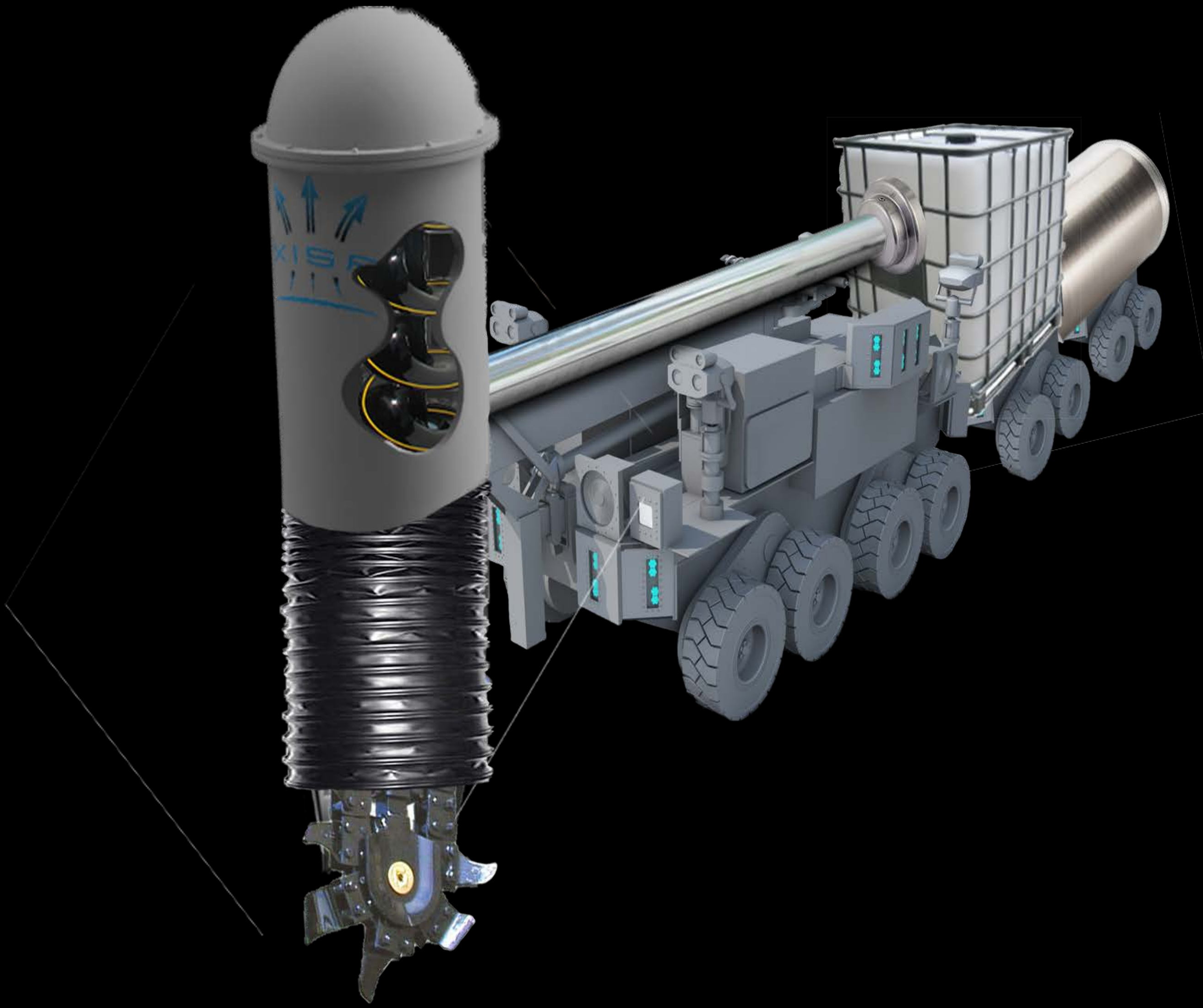
Art Work Credit: NASA

Solar Dynamic Components



Art Work Credit: NASA

WaterWitch Lunar Regolith Processing



Evolved Surface-to-Surface Beaming

Art Work Credit: XISP-Inc derived from NASA

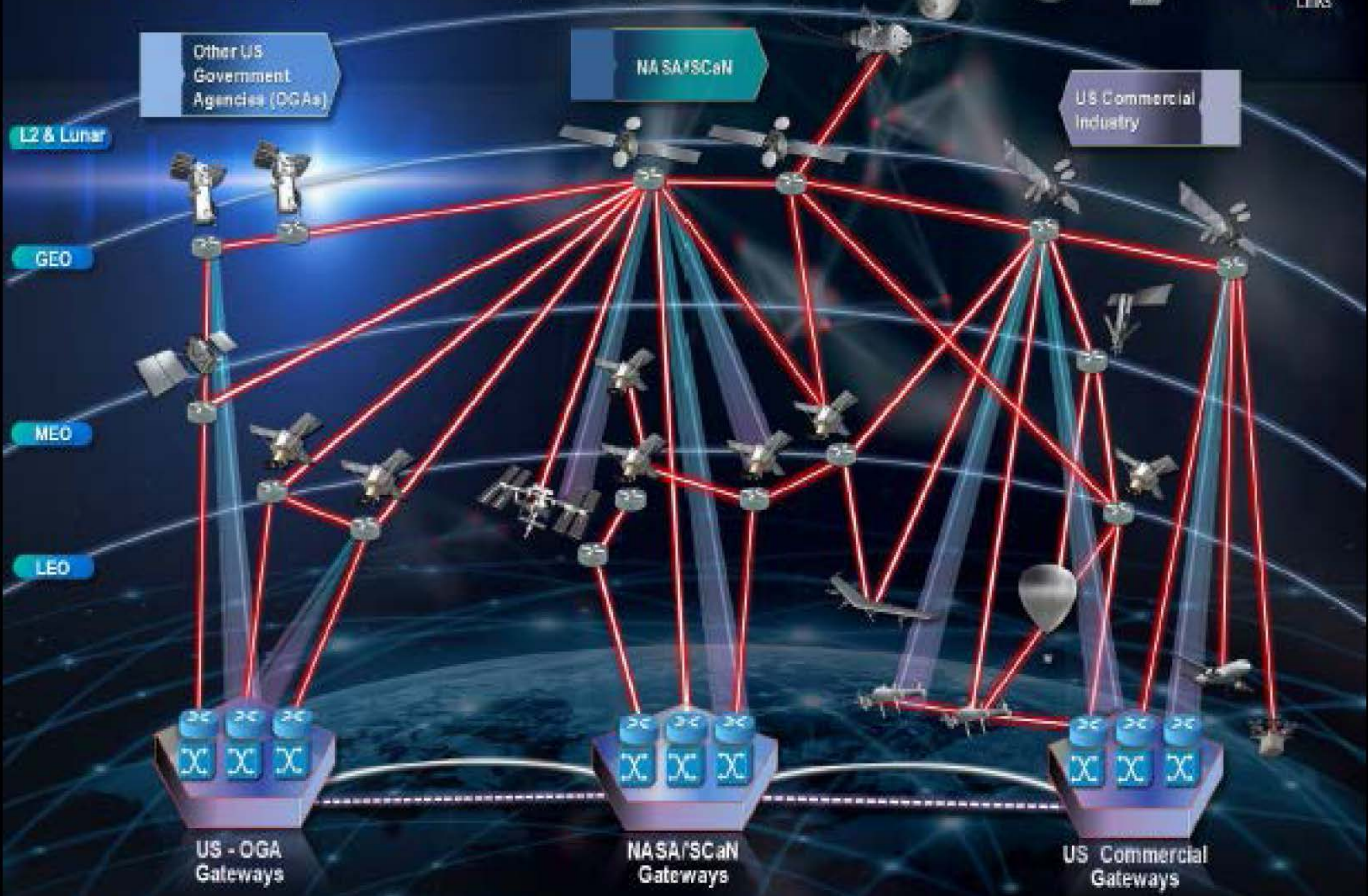
Interoperable Network Communications Architecture (INCA)

INCA elements can support:

- Enhanced automated/autonomous Communications & Navigation state models,
- Facilitate Situational Awareness of Cislunar Space
- 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.

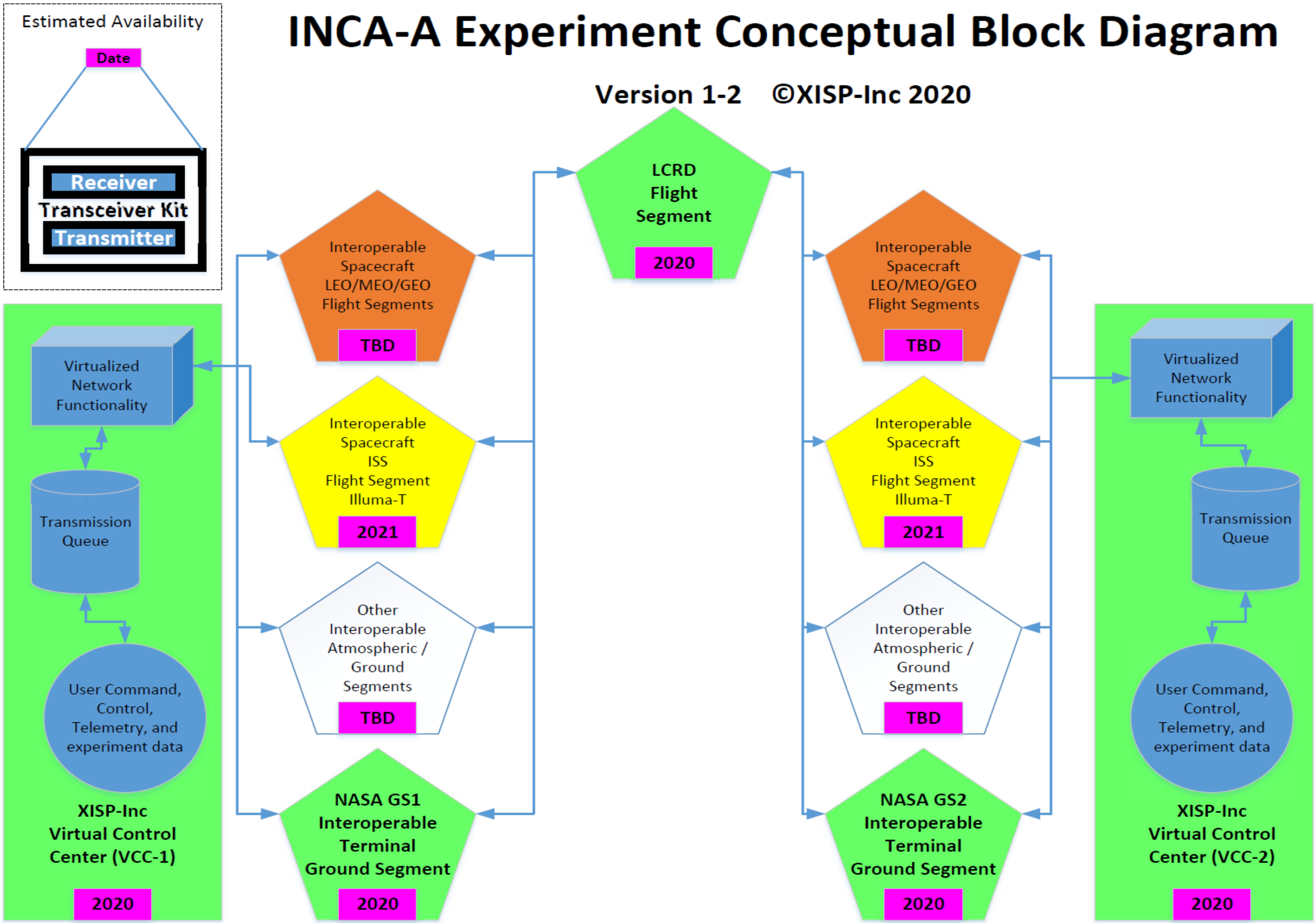
Power beaming requires bi-directional control links so by definition ancillary services are integral to the system design.

Our Vision Fully Connected Interoperable Space Domains



INCA-A Experiment Conceptual Block Diagram

Version 1-2 ©XISP-Inc 2020



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	

Commercial Space Power & Ancillary Services

- Integrated power & communications infrastructure using common 5G/6G technology enables leveraged investment
- Early technology and infrastructure investments will enable evolving space power and ancillary services utilities
- 5G/6G is an implementation paradigm, not an aspiration
  - *Ubiquitous services that scale to demand*
    - Internet of Things (IoT) to primary network trunk lines
  - *Use of Quality of Service (QoS) based routing*
    - Performance, Availability, and Security
  - *Frequency Agnostic to maximize QoS*
    - mm through eye safe optical wavelengths
  - *Security by Design*
    - Seamless implementation of ipSEC, dnsSEC, and WaveSEC

Commercial Space Power & Services

- Interoperable Network Communication Architecture (INCA)
  - Power – harvesting to wireless trunk lines
  - Ancillary Services – Data, Communications, Navigation, Time
  - Implements Delay/Disturbance Tolerant Networking (DTN)
  - Virtualized functions operate on pool of common hardware
  - Cognitive Software Defined Radio enables network discovery
  - Dynamic scheduling enables on demand services
  - Interoperable on demand services create premium market opportunities
- Support an emerging Cislunar marketplace driven from LEO out
  - Acceptance Driven Customers
  - Variable QoS serves flat rate customers, volume markets
  - QoS Driven Customers
  - Pay for QoS serves premium customers, vertical markets
  - Scales from ISS proximity operations, to LEO small sats, to GEO immortal platforms

Non-Technical Challenges & Opportunities

- 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.

- Geopolitical

– Make International Cooperation/Collaboration real.