Power and Ancillary Services Beaming Reducing the Systems Engineering to Practice

Lunar Surface Innovation Consortium Power Beaming Workshop
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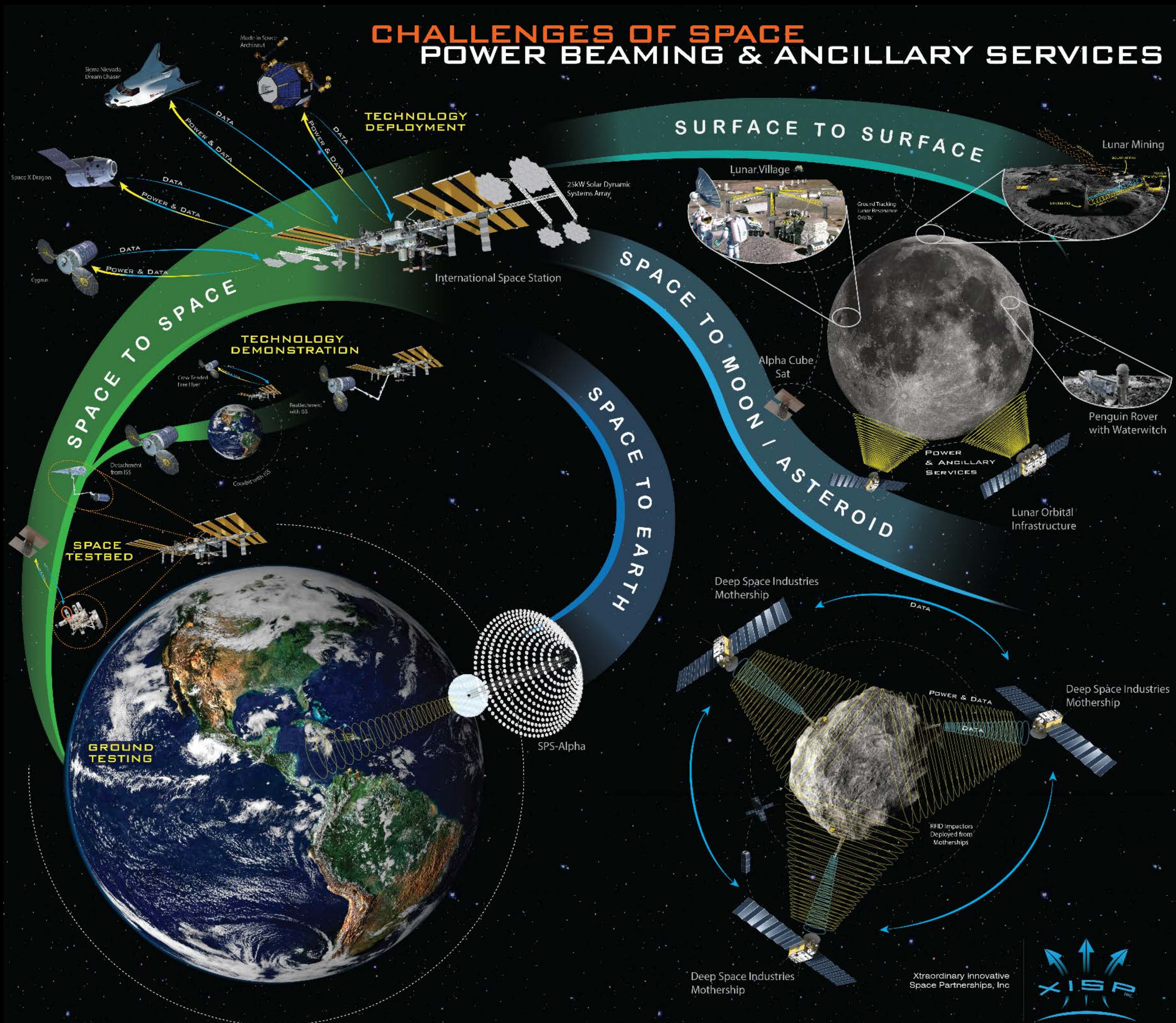


CHALLENGES OF SPACE
POWER BEAMING & ANCILLARY SERVICES
Made in Space Archinaut
Sierra Nevada Dream Chaser
Space X Dragon
Cygnus
DATA
POWER & DATA
TECHNOLOGY DEPLOYMENT
2.5kW Solar Dynamic Systems Array
International Space Station
SURFACE TO SURFACE
Lunar Village
Lunar Mining
SPACE TO SPACE
TECHNOLOGY DEMONSTRATION
Crew Tended Free Flyer
Reattachment with ISS
Coorbit with ISS
Detachment from ISS
SPACE TESTBED
GROUND TESTING
SPACE TO EARTH
SPS-Alpha
SPACE TO MOON / ASTEROID
Alpha Cube Sat
Power & Ancillary Services
Penguin Rover with Waterwitch
Lunar Orbital Infrastructure
Deep Space Industries Mothership
Deep Space Industries Mothership
Deep Space Industries Mothership
RFID Impactors Deployed from Motherships
Xtraordinary Innovative Space Partnerships, Inc
XISP Inc.

Space Solar Power Challenge Matrix

TRL Advancement

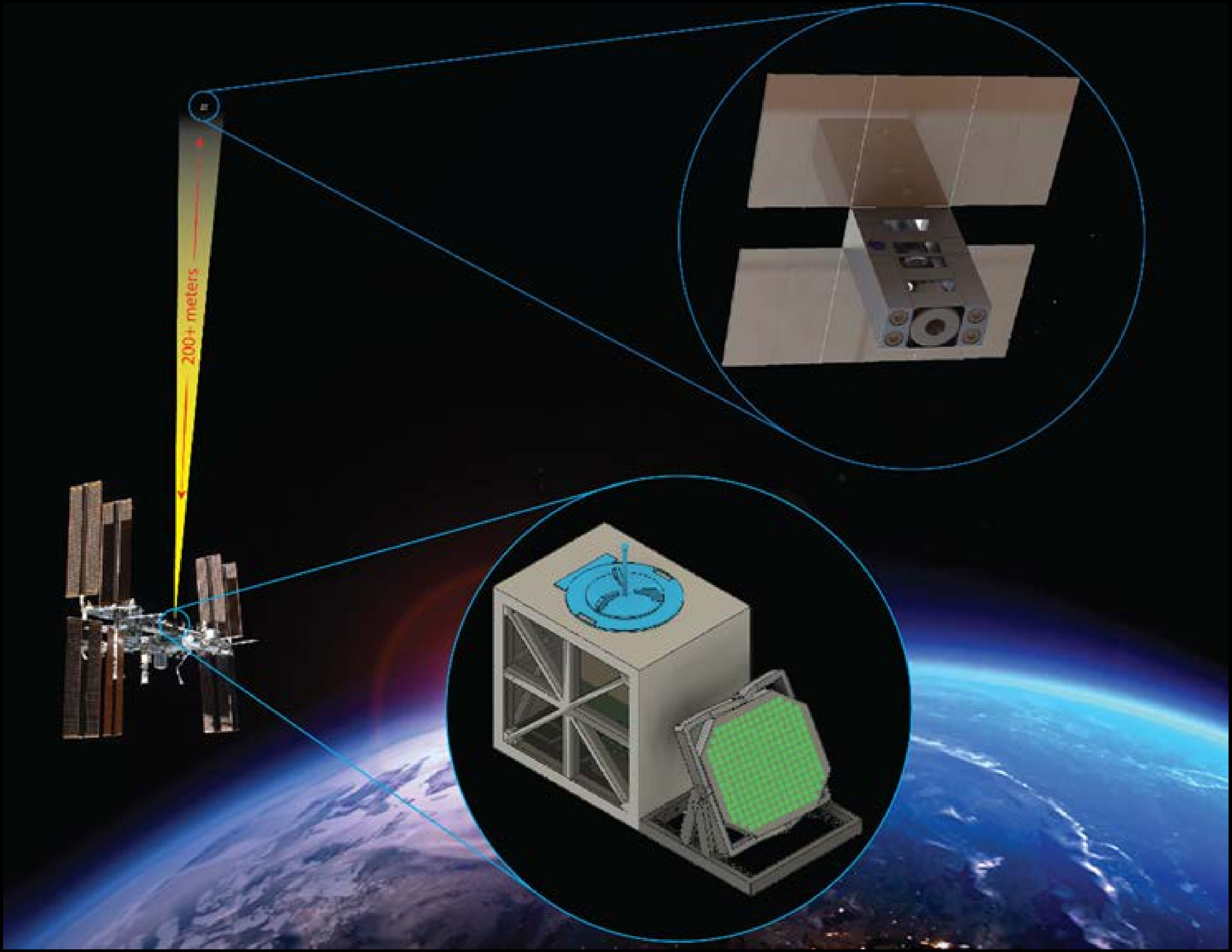
Relative Value of Delivered Power

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

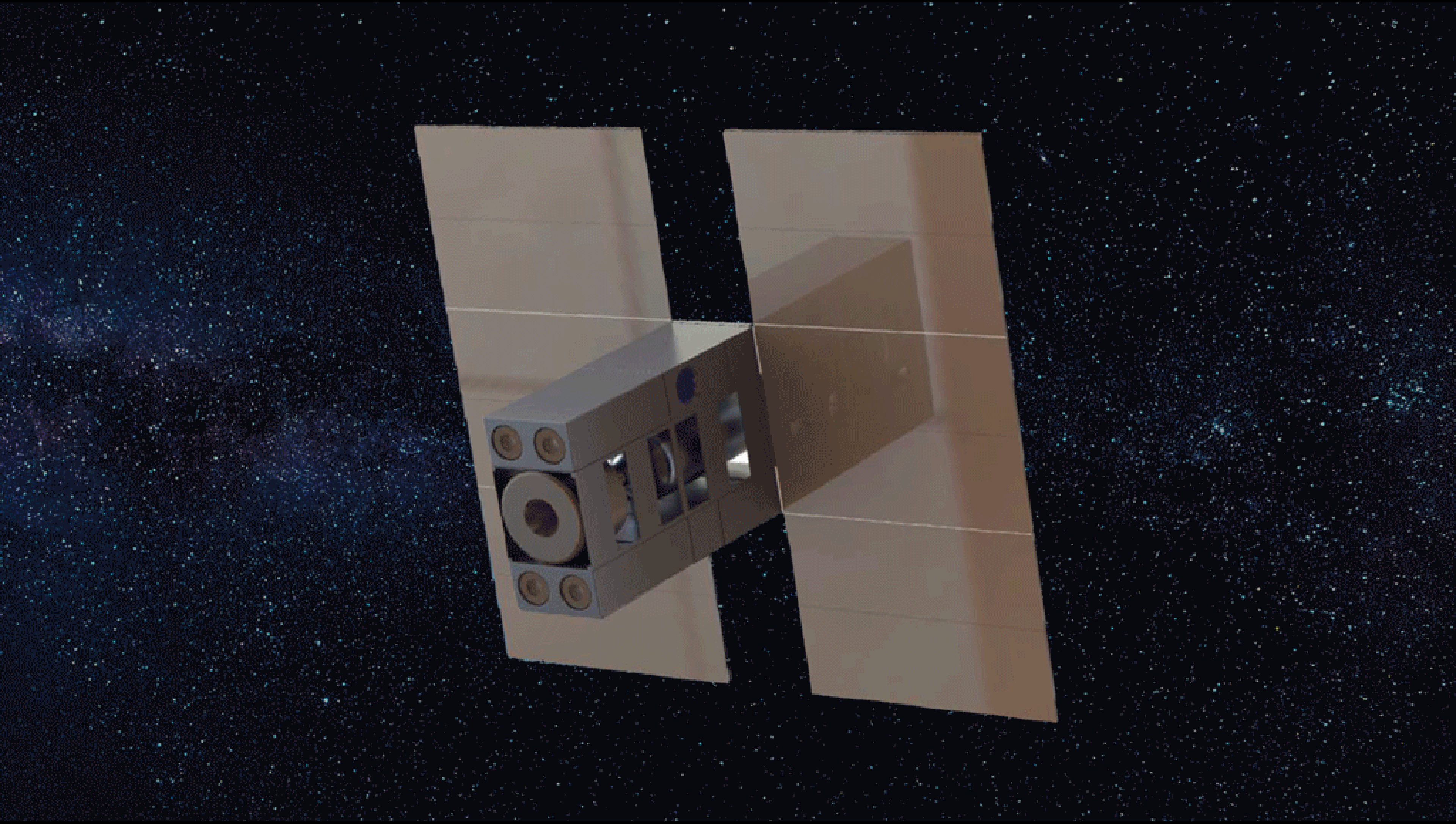
SSPB - Mission Overview

- 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 Mission Overview



SSPB Mission Overview



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)

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

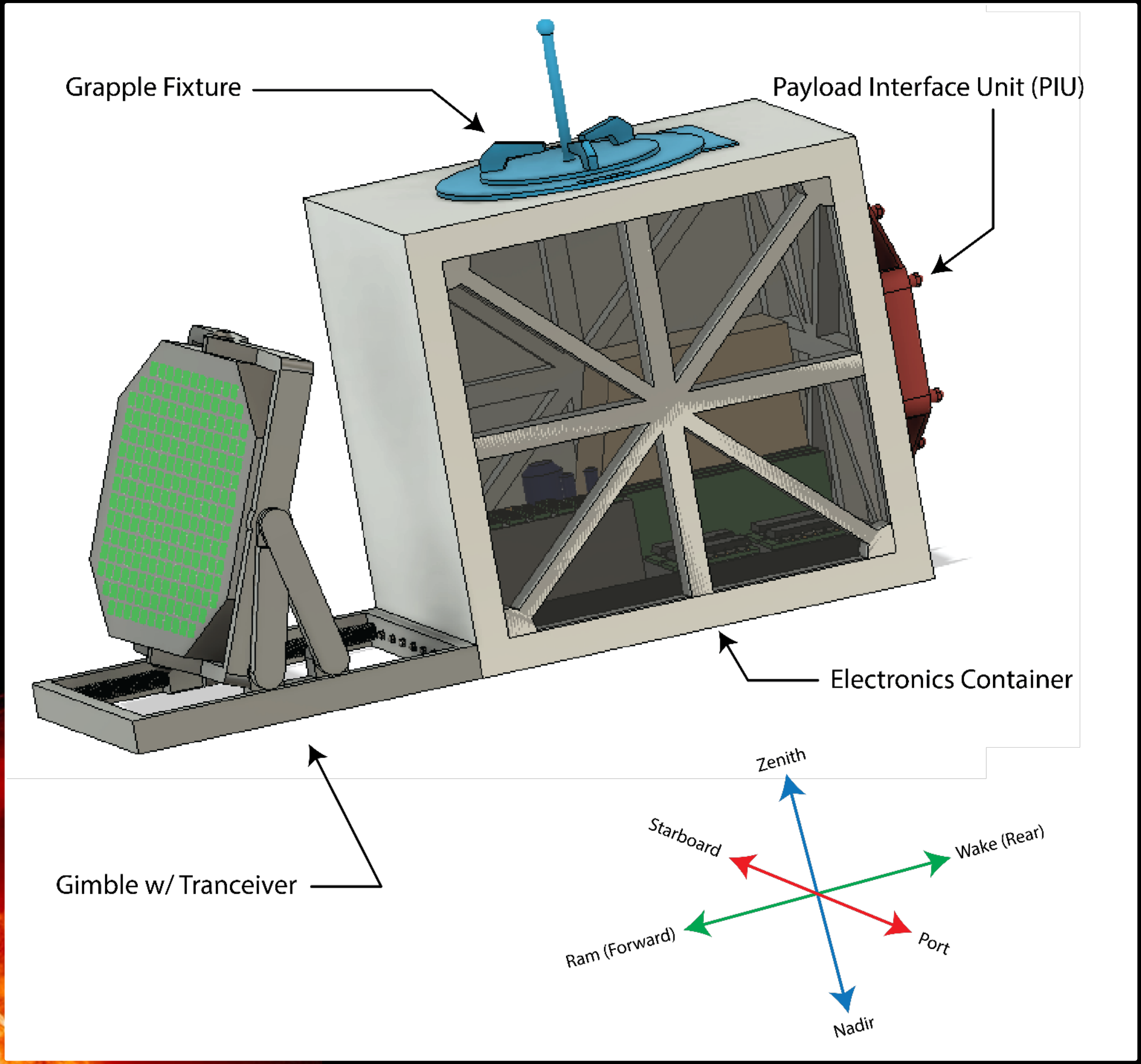
	Power Density (Watts/cm^2)	Power Density (Watts/cm^2)	Power Density (Watts/cm^2)
	P_d	**P_d**	**P_d**
	Case 1 @26.5 GHz	**Case 2 @36 GHz**	**Case 3 @95 GHz**
Table 1. Power Density with D=200 m, P_t= 3000 W and A_t = 1642 cm^2	0.00964	0.01774	0.12331
Table 2. Power Density with D=200 m, P_t= 6000 W and 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}

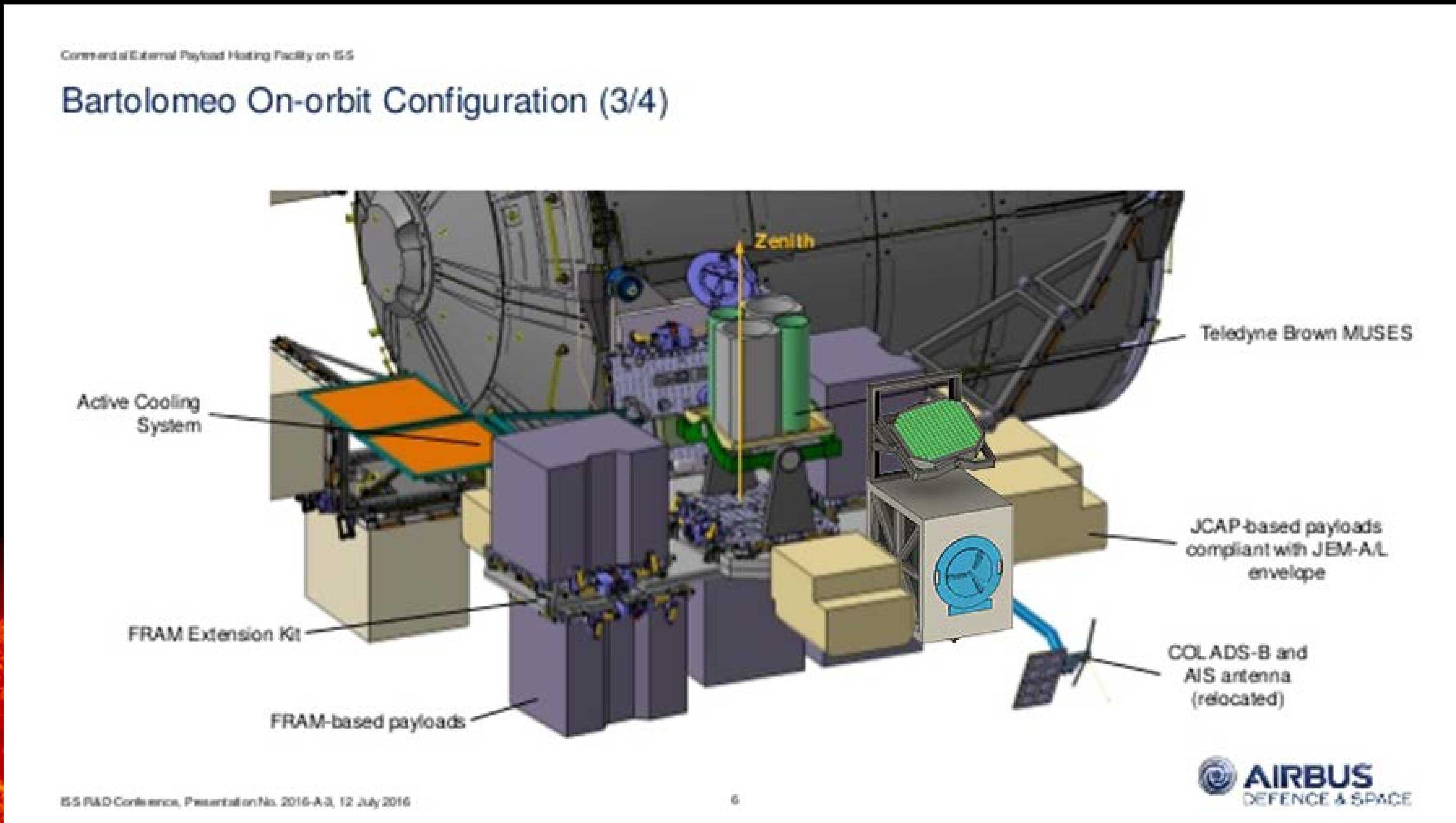
Table 5. Comparing Beaming Power Density and the Solar Constant

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

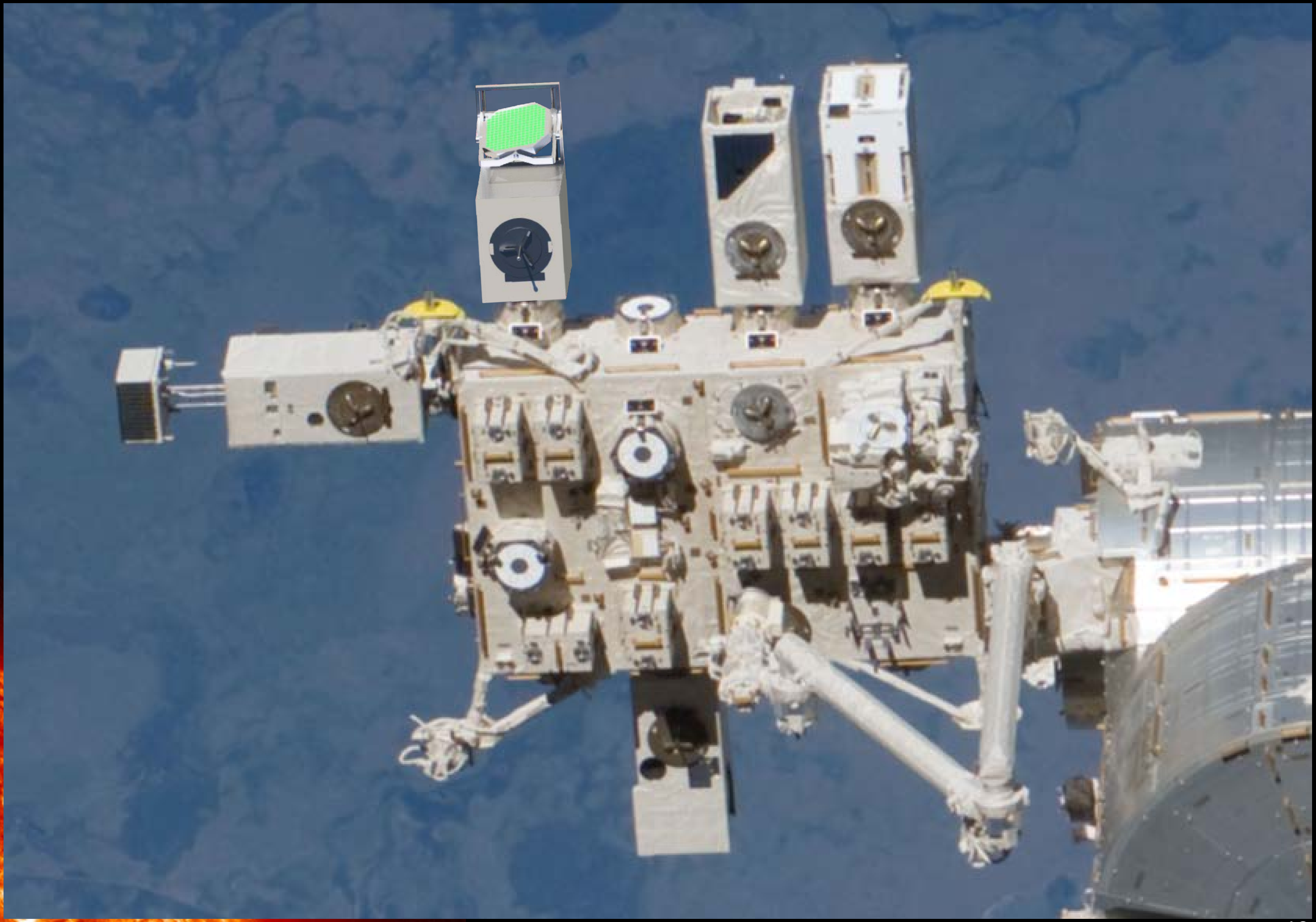
SSPB Transceiver Preliminary Design Isometric



Barto Exposed Facility Accommodations



JEM Exposed Facility Accommodations



Cygnus & Dragon Free flyers

THE VALUE OF PERFORMANCE.
NORTHROP GRUMMAN

SPACEX

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 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

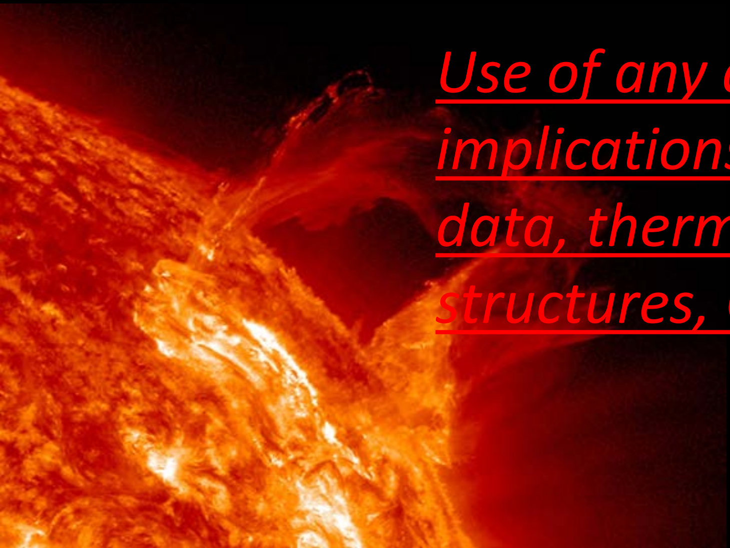
Technological Challenges

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

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

Technological Challenges -2

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



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

Technological Challenges - 3

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

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

– Jan L.A. van de Snepscheut
computer scientist

Additional Challenges - 3

- <u>Economics</u>

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

– Each addressable market has different fundamental figures of merit.

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

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

- <u>GeoPolitical</u>

– Make International Cooperation/Collaboration real.

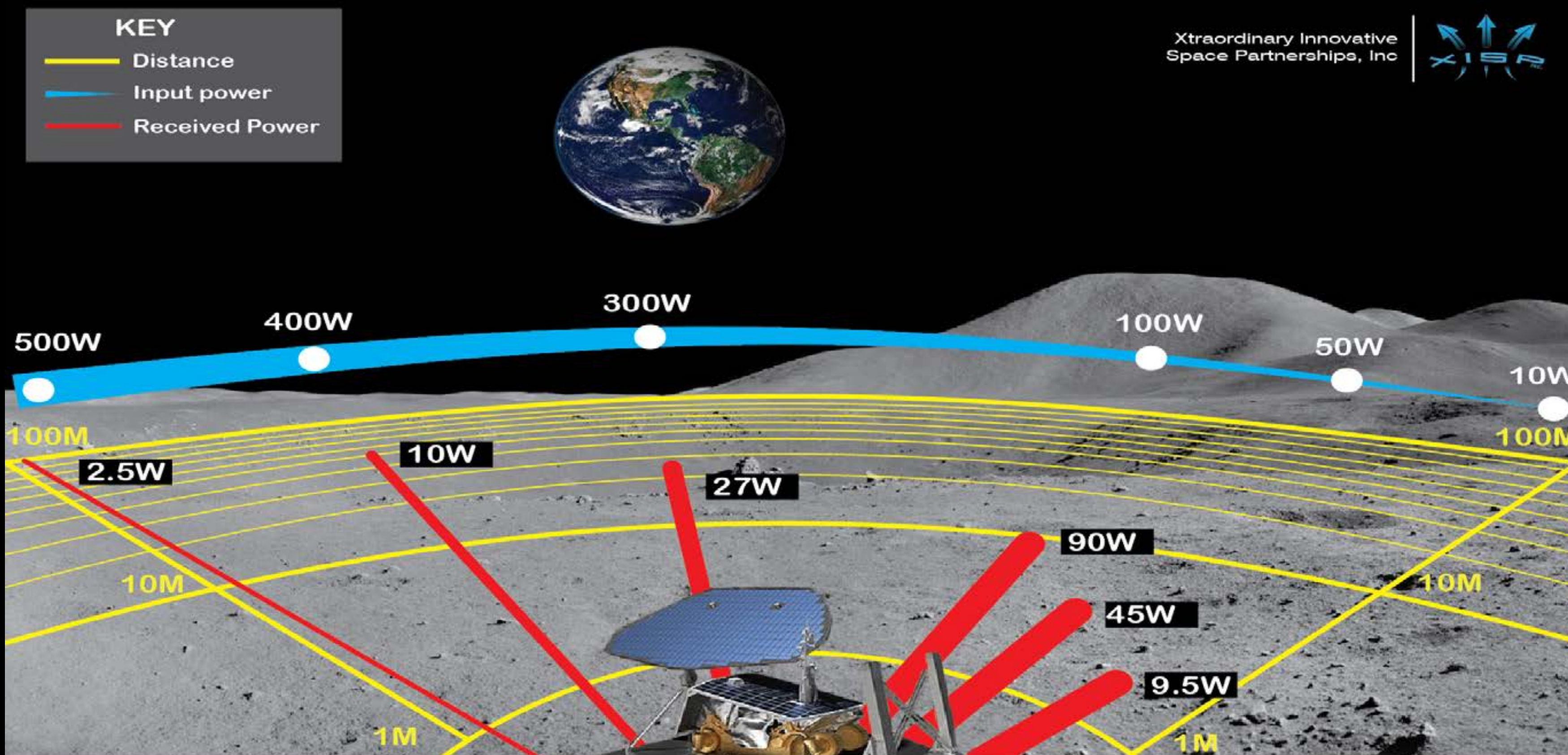
REPRESENTATIVE TIMELINE

Energy TD^3 Iterative and Recursive Milestones

Technology Development → Technology Demonstration → Technology Deployment

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

Xtraordinary Innovative Space Partnerships, Inc



XISP-Inc Team Power & Ancillary Service Beaming Lunar Lander Payload Concept

Key Variables:

Frequency = 92 GHz
Primary Transceiver Aperture Area = .2 m^2
Primary Transceiver DC to RF Efficiency = 20%
Secondary Transceiver Aperture Area = .049 m^2
Secondary Transceiver RF to DC Efficiency = 50%
Distance = 1 to 100 m
Lunar Lander Input Power = 10, 50, 100, 300, 400 and 500 W
Conservative estimations of performance metrics based on measured component data were used
Payload Received Power is shown for five representative input power + distance cases

Actual Payload Power received would be optimized by adjusting variables for each application

Ancillary Services up to 40 Gbps have been demonstrated using higher order modulation schemes

Free-path propagation loss included


Lunar.Village

Next Steps

- Space Solar Power and ancillary services Beaming (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 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

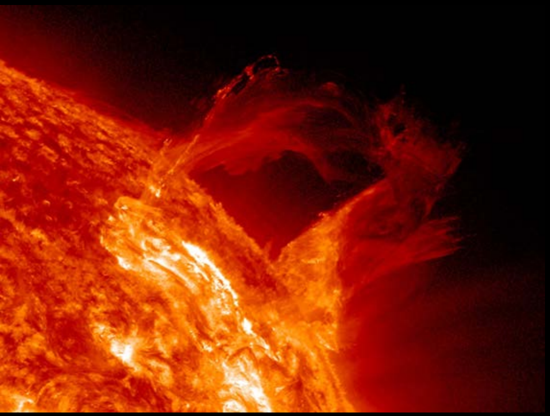
     space-to-space, surface-to-surface, space-to-lunar/infrastructure surface, and space-to-Earth

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

What's Next?

Lunar Power & Light Company

an XISP-Inc Consortium



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

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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