Challenges of Space Power & Ancillary Services Beaming: Key to Opening the Cislunar Marketplace

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Space Power Beaming & Ancillary Services

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Space Solar Power Key Considerations

- Space Solar Power is an applied engineering problem and an economics problem.
- Applications have significant systems engineering and economic challenges in each venue that must be successfully addressed.
- Each venue has different fundamental figures of merit which define their value proposition.
- Operational capabilities are best realized by leveraging a combination of technology development "Push" and mission requirements "Pull".
- Each increment of public and/or private investment should lead to an operational capability.
- Work Vectors: Technology Development ➔ Demonstration ➔ Deployment and Space-to-Space ➔ Surface-to-Surface ➔ Space-to-Alt Surface ➔ Space-to-Earth

Space Solar Power Key Variables

- Cost/Economics (initial cost to first power, LCOE, market viability, anchor customers),
- Frequency/Wavelength (microwave to eye-safe optical),
- Voltage/Amperage (input, output, transforms)
- Distance (near field, boundary regions, far field),
- Magnitude (power level supporting applications, scalability)
- 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-to-Space Power Beaming (SSPB) Hypothesis

XISP-Inc has hypothesized that unbundling/disaggregating power systems (i.e. the separation of power generation, transmission, control, storage, and loads) can:

- reduce spacecraft complexity, mass and/or volume
- allow reallocation of spacecraft mass and/or volume
- alter the cadence of spacecraft mission operations
- reduce or eliminate solar pointing requirements
- impart additional delta-V to spacecraft/debris
    - indirectly (power augmentation)
    - directly (momentum transfer)

Work Vectors / Venues	Space Solar Power Problem Space: Technology Development – Ground	Space Solar Power Problem Space: Technology Development – Space	Space Solar Power Solution Space: Operational Capability/Applications – Technology Demonstration	Space Solar Power Solution Space: Operational Capability/Applications – Technology Deployment
Space - to - Space	• Cognitive SDR Transceiver • Converged Electro/Optics • W Band & Optical Apertures • Piecewise Efficiency • Reflectarray Rectenna • Beam Forming • Management Operations Control Applications (MOCA)	• ISS Mounted Transceiver • Deployable Rectenna • 6U Flight Test Article • Optimized Frequencies • End-to-End Efficiency • Scaling/Modularity (Gen, Trans, and Control) • 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	• 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	• Powered Rover • Powered Prospector • Powered Miner • Volatile/Metal Separation	• Power & Ancillary Services Beaming - Survive the Night • Volatiles Mining Demo • Propellant Depot Demo • Metals Mining Demo	• Dispatchable Power & Ancillary Services • 24x7 Operations Support • Kilowatt to Megawatt Scale Services
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)	• 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
Sierra Nevada Dream Chaser
Made in Space Archinaut
Space X Dragon
Cygnus
DATA
POWER & DATA
TECHNOLOGY DEPLOYMENT
SURFACE TO SURFACE
Lunar Mining
Lunar Village
25kW Solar Dynamic Systems Array
International Space Station
SPACE TO SPACE
SPACE TO MOON / ASTEROID
SPACE TO EARTH
TECHNOLOGY DEMONSTRATION
Crew Tended Free Flyer
Redeployment with ISS
Detachment from ISS
Docking with ISS
Alpha Cube Sat
Penguin Rover with Waterwitch
POWER & ANCILLARY SERVICES
Lunar Orbital Infrastructure
SPACE TESTBED
GROUND TESTING
SPS-Alpha
Deep Space Industries Mothership
RFID Impactors Deployed from Motherships
Xtraordinary Innovative Space Partnerships, Inc
XISP INC.

SSPB Mission Overview

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 Functional Block Diagram

SSPB Phase I & Follow-on Concept of Operations

SSPB Mission Overview

Communications
Receiving & Transmitting
Microwaves
Receiving Only (Power)
Visible Light
Receiving Only (Power)
Feed & Receiver
Layer 1 - Solar Panel
Layer 2 - Rectenna
Layer 3 - Communications Reflector
Reflecting Elements

SSPB Mission Overview

SSPB Transceiver Preliminary Design Isometric

Barto Exposed Facility Accommodations

JEM Exposed Facility Accommodations

Power Density* versus the Solar Constant

	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}		

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

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

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

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.

Cygnus & Dragon Free flyers

THE VALUE OF PERFORMANCE.
NORTHROP GRUMMAN

SPACEX

SSPB Phase II - Technology Deployment Components

Power Generation, Storage, and Distribution

Brayton Cycle Heat Engine Block Diagram (Simple)

Brayton Cycle Hear Engine Block Diagram w/Process Heat Options

SSPB Transceiver Preliminary Design Isometric

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

Lunar.Village

XISP-Inc WaterWitch Lunar Regolith Volatiles and Ore Prospecting

Early Space Station Design w/Solar Dynamic

LaRC/GRC 2kW Solar Dynamic Test

Solar Dynamic Components

Energy TD³ Iterative and Recursive Milestones

Technology Development → Technology Demonstration → Technology Deployment

Space Solar Power	2019	2022	2025	2029	2038	2047
	ISS TD³	LEO TD³	GEO TD³	GEO TD³	GEO TD³	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		
• 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	→ $$$	→ $$$$	
• Space In situ	Platform Model	Platform TD³	Platform Ops	→ $$$	→ $$$$	
• Luna-to-Luna	Spectrum Model	Spectrum Apply	Spectrum Allocation			
• Earth-to-Earth	Orbit Slot Model	Orbit Slot Apply	Orbit Slot Allocation			
	LP&L Seed/Angel	LP&L Series A/B/C	LP&L IPO	→ $$$	→ $$$$	
	Co-orbiting Tests	Co-orbiting Labs	Co-orbiting Facilities	→ $$$	→ $$$$	
		Lunar Test(s)	Lunar Operations	→ $$$	→ $$$$	
		NEO Test(s)	Asteroidal Assay	→ $$$	→ $$$$	

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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 space-to-space, space-to-lunar/infrastructure surface, and space-to-Earth
- Commercial space applications include:
  1. enabling expansion of operational mission capabilities,
  2. enhanced spacecraft/infrastructure design flexibility, and
  3. out-bound orbital trajectory insertion propulsion, and
  4. pave the way for the Lunar Power & Light Company.

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

Backup Slides

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 & 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 & 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 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 – Northrup 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

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.