XISP-Inc.

Space-to-Space Power Beaming (SSPB) Mission

SSPB (aka Radiant energy beaming)

- The ability to characterize, optimize, and operationalize end-to-end radiant energy beaming systems for the delivery of power and ancillary services to meet customer requirements for space-to-space applications is within our grasp.
- Such an endeavor constitutes an achievable Technology Development, Demonstration, and Deployment (TD^3) mission which can leverage assets drawn from multiple programs, agencies, commercial entities, universities, and non-profit organizations.
- The orchestration of the TD^3 effort to yield an extensible testbed allowing for the characterization of the key service variables, the demonstrable use of the technology to meet the requirements of some number of customers, and the evolution of the fielded systems to deployable infrastructure is a near term challenge that can be met.

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SSPB Mission Definition

- Unbundle spacecraft electrical power systems
- Provide beamed power and ancillary services as a utility
- Support further development of power beaming technology
- 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
- 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

This work addresses both real and perceived cost, schedule, and technical risks associated with Space Solar Power and ancillary services beaming across multiple venues including: Space-to-Space, Space-to-Alternate Surfaces, as well as the potential for Space-to-Earth applications.

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SSPB Technology Development Components

- Multi-band receiving antennas (rectennas) (Ka, W, and Optical)
- Optimized Multi-band transmitters (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

Technology development work leverages SSPB mission Consortium internal research and development efforts, and active development/production contracts as applicable.

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SSPB Technology Demonstration 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) with rectenna and active attitude control system/propulsion

The combination of the technology development work and the these demonstrations will provide for Technology Readiness Level (TRL) advancement to TRL 8/9

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SSPB Technology Deployment Components

- ISS Co-orbiting Radiant Energy Beaming (200 m to TBD km)
- 6U Cubesat MSC released test with optimized transmitter & rectenna
- OrbitalATK Cygnus pressurized logistics carrier test with optimized transmitter & rectenna
- NanoRacks Commercial Airlock/free-flyer test with optimized transmitter & rectenna (proposed)
- Made In Space manufacturing cell test with optimized transmitter & 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 ancillary utilities delivery will progress as systems are fielded.

➔Emergency ➔ Servicing ➔Augment ➔Backup ➔Primary

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SSPB Mission Variables

- **Frequency** (microwave to eye-safe optical),
- **Distance** (near field, boundary regions, far field),
- **Magnitude** (individual end user scale <10 kW, industrial scale 10 kW to 100 kW, military scale > 100 kW),
- **Duration** (pulse, scheduled, continuous),
- **Availability** (on demand, scheduled, prioritized, by exception),
- **Security** (misuse, interruption, destruction), and
- **Performance** (net transfer, end-to-end efficiency, piecewise efficiency, effective difference).
- **Ancillary Services** (Communications, Data, Navigation, Time)
- **Testing** (Ground, captive on-orbit, and co-orbiting)

All mission variables must be traded on piece wise iterative basis and as well as recursively on an end-to-end basis.

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SSPB Work Breakdown Structure

- Mission Development ➔ *XISP-Inc*
- Systems Engineering ➔ *XISP-Inc, Bus Vendor, & Consortium*
- Flight Test System Satellite Bus ➔ *Multiple Proposals In hand*
- ISS Transmitter Frequency Agnostic SDR w/Phased Array Transmitter Aperture(s) ➔*Raytheon + Consortium teaming**
- Flight Test System Payload "Rectenna" ➔*Raytheon, Immortal Data + Consortium teaming*
- Integration, Verification & Validation ➔ *XISP-Inc, Bus Vendor, Raytheon, NRL, & Consortium teaming*
- Launch & ISS Accommodations ➔ *Nanoracks & NASA*
- Operations ➔ *XISP-Inc, Immortal Data, Orbital ATK, & Consortium teaming*

**Consortium teaming is the internal make versus buy trade of all applicable subsystems/components/services*

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SSPB Mission Resources & Schedule

- NASA has determined*:
  - *The XISP-Inc SSPB mission is classified as a Commercial Mission*
  - *"Space-to-space power beaming is of interest to NASA and has the potential to affect a wide range of missions and is a potential key element of space infrastructure for the future."*
  - *"Overall, the [XISP-Inc SSPB] proposal is relevant to NASA's exploration goals and reflects the involvement of a team with appropriate experience."*
- NASA's level and type of participation (direct and indirect) is under negotiation – No direct funding resources have been provided to date
- NASA has acknowledged and is cognizant of the formal XISP-Inc ISS payload broker (CASIS) resource request in process (partial mission development funding, integration, launch, ISS equipment, and ISS crew time).
- Latest SSPB Mission Total Cost as proposed to NASA STMD (cash & in-kind funding) < $13 Million
- Commercial investment is first money (XISP-Inc ~$1 Million cash & in-kind)
- FY 2018 Mission development complete, 2019-2022 execution schedule

* Per NASA evaluation of latest XISP-Inc SSPB ISS NRA 2017 Proposal

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SSPB Test Bed Experiments

- End-to-End & Piecewise Efficiency Optimization
  - DC ===> Microwave/Optical
  - Beam Forming, Transmission, Rectenna
  - Microwave/Optical ===> 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?

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SSPB & Commercial Evolution - 1

- Repurpose Cygnus Pressurized Logistics Carriers as crew tended co-orbiting labs with fault tolerant power and ancillary services for some number of cycles.
- Support other co-orbiting crew-tended space manufacturing demonstrations & elements
- Lunar Power & Light Company – a Cislunar power and ancillary services (power, communications, data, navigation, time) 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

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SSPB & Commercial Evolution - 2

- Asteroidal Assay
  - Co-orbiting motherships with landed sensors
- ISS & Commercial Co-orbiting Free-flyers
  - Micro-g manufacturing cells
  - Special testing/safety regimen lab space
- 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

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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

Theoretical Limits & Other Considerations:
- Diffraction
- Thermal capacity/heat tolerance
- Electromagnetic Environment
- Navigating Frequency Allocation & Use Issues

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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)

Both component work and an End-to-End Testbed are needed

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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

Source power-to-beam efficiency of 43 percent has been demonstrated and reported in open literature.
This is a further indication that both component work and an End-to-End Testbed are needed.

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Power Density* vs the Solar Constant

$$P_d = A_t P_t / \lambda^2 D^2$$

	Power Density P_d (Watts/cm^2) Case 1 @26.5	Case 2 @36 GHz	Case 3 @95 GHz
Power Density with D=200 m, P_t= 3000 W and A_t = 1642 cm^2	0.01	0.02	0.12
Power Density with D=200 m, P_t= 6000 W and A_t = 1642 cm^2	0.02	0.04	0.25
Power Density with D=200 m, P_t= 3000 W and A_t = 10000 cm^2	0.06	0.11	0.75
Power Density with D=200 m, P_t= 6000 W and A_t = 10000 cm^2	0.12	0.22	1.50

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}

Theoretical Power Density (P_d) of beam is over an order of magnitude greater than I_{sc} for Case 3 @95 GHz

*More detailed calculations using Collection Efficiency methods are provided in Barnhard, Gary Pearce; Space-to Space Power Beaming AIAA Space 2017. Power density is calculated using far field equations per William C. Brown, et al. (1992)

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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, not well understood
- Moreover, there is no 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.

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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.)

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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

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Next Steps

- SSPB is a XISP-Inc commercial mission recognized by NASA.
- NASA is participating through a combination of in-place (NASA ARC) and proposed (NASA HQ/CASIS) Space Act Agreements.
- Formal request for support is under review with CASIS.
- NASA direct support to accelerate and/or add additional milestones when opportunities emerge is being applied for.
- Additional partners/participants are being sought in the commercial, academic, non-profit, and government sectors.
- Opportunities for international cooperation leveraging the ISS Intergovernmental Agreement are being explored and developed.

Use of ISS helps ensure that this is an international cooperative/collaborative research effort.

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Conclusion

- Successful demonstration of SSPB in LEO could:
  - Reduce perceived cost, schedule, technical risk of SSP
  - Pave the way for SSP use in space-to-space, space-to-lunar / infrastructure surface, and space-to-Earth applications
- The confluence of interests formed as a unique public-private partnership can yield a consortium which proves out the economies of scale associated with power and ancillary services generation and distribution in space, the Lunar Power & Light Company.
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