Space-to-Space Power Beaming (SSPB) -- A Commercial ISS Technology Development, Demonstration, and Deployment (TD^3) Mission

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Abstract:

One of many paths forward for hastening the development of viable applications of space solar power technology is through focused incremental Technology Development, Demonstration, and Deployment (TD3) efforts. This paper addresses one such effort that is moving forward through mission development -- Space-to-Space Power Beaming (SSPB), a commercial International Space Station (ISS) Technology Development, Demonstration, and Deployment (TD3) mission. This paper summarizes the SSPB mission genesis building on foundational research in the field, the mission development work accomplished to date, the evolving concept of operations, and the current mission status. The SSPB mission is intended to help mitigate cost, schedule, and technical risk associated with the short, mid, and long term application of space power and ancillary services beaming technology. This mission involves significant technology development, demonstration, and deployment elements, intended to be orchestrated and implemented in a manner that delivers significant value to some number of customers co-orbiting with the International Space Station (ISS) as well as serving as a testbed environment for more expansive SSPB TD3 efforts. This paper lays out the TD3 objectives associated with the unbundling of space power systems (i.e., the separation of power generation, transmission, distribution, and loads) and how the authors and their team intend to use that unbundling process to build a bridge over what has euphemistically been called the "technology development valley of death". The latest estimated deliverable power density and power received values based on the collection efficiency calculations (which have correlated to ground tests by other research efforts) are provided. Power received is calculated for a range of rectenna sizes at a 200 m distance for: multiple frequencies, potential ISS input power levels, and selected transmit aperture areas. In addition, a comparison between estimated delivered power density and the Solar Constant is provided for the orbital distance of immediate interest. The calculated values clearly show that the low end of Ka band, with a delivered power density an order of magnitude less the than Solar Constant is very benign. The high end of Ka band can actually meet some customer requirements at best at a small multiple of the Solar Constant. However, W band frequency can provide a power density an order of magnitude or higher than the Solar Constant. The challenge in all instances is engineering systems with an end-to-end efficiency which is satisfactory and sufficient for the application. The ability to provide power when and where you need it is essential to virtually all aspects of human endeavor, and is enabling for any form of space settlement. Space solar power technology holds the promise of being one of the few large scale energy generation options which can scale to meet the growing electrical energy demand of the world. This mission is a unique opportunity to foster the development of space-to-space power beaming by leveraging ISS resources to create a SSPB testbed environment on and near the ISS that supports the development of frequency agnostic radiant energy beaming technology. This paper provides a substantive update on the mission development work that has been accomplished since the original paper was presented at AIAA Space 2016.

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Nomenclature

I_{sc} = Solar Constant at 1 AU = 0.1367 W/cm^2
P_d = power density at the center of the receiving location, W/cm^2
P_t = total radiated power from the transmitter, W
A_t = total area of the transmitting antenna, cm^2
A_r = total area of the receiving antenna (rectenna), cm^2
λ = wavelength, cm
D = separation between the transmitting and receiving antenna apertures, cm
P_r = power received at the rectenna, W
ζ = zeta is a value which relates the physical parameters of the power beaming system to the collection efficiency, dimensionless
W = diameter the area of an equivalent square rectenna, cm
D = diameter the area of an equivalent square transmitter antenna, cm
R = separation between the transmitting and receiving apertures, cm

I. Introduction

One of many paths forward for hastening the development of viable applications of space solar power technology is through focused incremental Technology Development, Demonstration, and Deployment (TD^3) efforts which serve to bridge the "technology development valley of death". This mission seeks to help mitigate the cost, schedule, and technical risk associated with the short, mid, and long term applications of space power and ancillary services beaming. The potential of space solar power technology has been examined in some detail by other researchers providing both a technical foundation and an inspiration to bring this work to fruition.[1-6] This mission provides both a testbed environment for the technology as well as power and ancillary services of demonstrable value to some number of customers co-orbiting with the International Space Station (ISS). This paper lays out the TD^3 objectives associated with the unbundling of space power systems (i.e., the separation of power generation, transmission, management, and loads)[7-24] to enable applications of Space-to-Space and Space-to-Alternate Surface Power Beaming that are mission enhancing if not mission enabling. We have a unique opportunity to foster the development of space-to-space power beaming by leveraging ISS resources to create a space-to-space power beaming testbed environment on and in the vicinity of ISS. This work can be mission enhancing if not mission enabling for a range of Earth facing, space operations/development, and space exploration missions. Furthermore, this work can develop into space electrical and ancillary services as a commercial utility infrastructure. Accordingly, this work reinforces the United States leadership in the global high-tech marketplace as well as providing extraordinary opportunities for international cooperation and collaboration.

II. Mission Definition

The XISP-Inc Space-to-Space Power Beaming (SSPB) TD^3 mission, is a precursor to a Cislunar electrical power and allied utilities (communications, data, navigation/time) service, the Lunar Power & Light company (LP&L). The intention of the LP&L Company is to address markets for power and ancillary utilities (i.e., communications, data, navigation, and time) from the Karman line (100 km) through to the surface of the Moon.

Based on the hypothesis that there are economies of scale to be gained with respect to power generation, transmission, and distribution in space. An unbundled power system (separating power generation, transmission, distribution, control, and loads) where transmission and/or distribution occurs via a radiant energy beam can provide customers new mission-enhancing/mission-enabling technologies for meeting their power and other ancillary utility requirements, as well as delivering a compelling Return On Investment (ROI) to investors.

This work also 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.

The Technology Development components of the SSPB TD^3 mission are:

1) Systems/Subsystem Related:
   - o Multi-band receiving antennas (rectennas) (Ka band, W band, and Optical)
   - o Optimized Multi-band transceiver (Ka band, W band, and Optical)
   - o Multi-band phased array transmission apertures (Ka band, W band, and Optical)
   - o Radiant energy beaming control and safety interlock system
   - o Water based thrusters for propulsion and active attitude control system

2) Ancillary Utility Related:
  - Power/Data/Communications/Navigation/Time Multiplexing within radiant energy beams
  - Power and allied utility waveforms for Software Defined Radios (SDR)
  - Converged Radio Frequency & Optical SDR electronics

3) Intersecting XISP-Inc Missions:
  - Interoperable Network Communications Architecture (INCA) – (interoperable communications networks to accommodate customer ancillary utility requirements)
  - Management Operations Control Applications (MOCA) – (near real-time state models, NASA ARC Mission Control Technologies OpenMCT software suite)
  - Alpha Cube Sat (ACS) – (advanced cubesat design: reflectarray rectenna design, SDR, integrated avionics package, thruster/attitude control systems, virtual operations center)
  - Halfway To Anywhere (HTA) – (bi-modal water and electric propulsion, Trajectory Insert Bus, low energy trajectory applications)

The Technology Demonstration components of the SSPB TD^3 mission are:

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

The Technology Deployment components of the SSPB TD^3 mission are:

1) ISS Co-orbiting Radiant Energy Beaming (50 m ➔ 1 km)
  - 6U Cubesat Mobile Servicing Center (MSC) captive test with existing or optimized transmitter
  - 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)
2) 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.
3) Power and allied utilities delivery will progress as systems are fielded.
  - Emergency ➔ Servicing ➔ Augment ➔ Backup ➔Primary.

The ISS is a unique resource for this TD^3 mission. It our optimal “testbed environment” that features microgravity, vacuum, temperature range, vantage point, as well as a combination of teleoperated, automated, crew-tended, and hands on crew operations that can be optimized for productivity. Furthermore, ISS provides the first “customers”, ISS co-orbiting systems which will require fault tolerant power and allied utilities to accelerate, enhance, or enable, the ultimate deployment of their systems.

Attempting, to simulate on the ground the operational testbed environment required for the characterization, optimization, and definition of the operational rules for using a radiant energy beam as part of an unbundled space electrical power system for supporting co-orbiting spacecraft is untenable on an integrated basis. Doing whatever ground tests are possible on a piecewise basis will be an integral part of the mission execution.

The ISS platform will provide a cost effective test-bed for future development, characterization and verification of more advanced beamed power technologies. In addition, the orbital location of ISS provides access to an ionospheric regime whose effects on wave propagation are not as well understood as those from either the atmosphere, or deeper regions of space, particularly at the frequencies and beam intensities in question.

The SSPB mission facilitates ISS co-orbiting systems by providing the fault tolerant power and ancillary utilities which allow for normal ISS operations. These co-orbiting systems will be able to accommodate additional experiments which are currently not feasible because they require more stringent microgravity conditions, beam pointing accuracy requirements, alternate safety protocols, and/or would otherwise interfere with ISS operations.

SSPB missions will be able to address markets in LEO, MEO, HEO, GEO, Libration/Trajectory Waypoints, Lunar Orbits, Lunar Surface, and asteroidal surfaces. These follow-on missions are unlikely to happen on as timely and/or cost effective basis without accomplishment of the SSPB TD^3 mission on ISS. A necessary precursor to these more advanced applications is the accomplishment of our proposed TD^3 mission.

SSPB will lower costs and establish a robust foundation for providing electrical and ancillary utilities in Cislunar space. A Space-to-Earth power beaming capability could provide power on demand anywhere on Earth within line-of-sight of a space-based power facility. On a small scale, this could enable low-impact human activities in off-the-grid areas, for research, tourism, or disaster relief. Large-scale power beaming from Space-to-Earth could provide energy on Earth without worries of releasing carbon or radioactive materials into the atmosphere, profoundly improving life for everyone on Earth.

The Space-to-Space Power Beaming (SSPB) mission is a NASA recognized XISP-Inc commercial mission proceeding under a combination of existing and pending NASA Space Act Agreement authority as well as evolving commercial, university, and non-governmental organization agreements.

A. What is the problem being addressed?

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

1) reduce spacecraft complexity and thereby reduce cost, schedule, and technical risk
2) reduce mass and/or volume required to accomplish a given mission
3) reallocate mass and/or volume to enhance or enable missions
4) indirectly impart additional delta-V along velocity vectors of choice to enhance or enable missions
5) foster the development of loosely coupled modular structures to enable:
    a. formation flying of multiple spacecraft (e.g., interferometric groups, swarms)
    b. distributed payload and subsystem infrastructure to simplify the accommodation of multiple plug-in and plug-out interfaces
    c. large scale adaptable space structures that minimize conducted thermal and/or structural loads.

Furthermore, by the realization of the above and taking advantage of the economies of scale power and ancillary services can be provided to range of Cislunar markets starting with the co-orbiting environment of the ISS.

B. What is the Economic Benefit and Commercial Relevance?

It is anticipated that the TD^3 mission will provide beamed power and allied utilities to ISS co-orbiting customers at a level sufficient to warrant the mission investment, and in the process retire both real and/or perceived cost, schedule, and technical risk associated with the evolved/scalable systems required for the next phase of investment. Accordingly, we anticipate that the TD^3 mission will lay the technological foundation for our Cislunar electrical power and allied utilities service, the Lunar Power & Light (LP&L) Company.

The capability to physically separate solar electricity generation from point-of-use will enable a wide range of applications, operations, and exploration missions not previously possible. By reducing constraints imposed by solar arrays we can realize mass, volume, increased sensor system efficiency, reliability and maintenance in a harsh operational environment.

Mission architectures are made possible for distributed payloads and sensors with application in disaggregated systems in Earth orbit and for demanding deep space missions. This is particularly useful for dust and shadow environments where sunlight may be blocked such as asteroid surface activities and dark lunar craters. Also, mission architectures are enabled for disaggregated spacecraft where portions of the “swarm” may experience shadow. Power beaming can be used large solar arrays are not desirable or feasible on the sensor platform due to spacecraft dynamics or thermal/structural loads. Cost-effective augmentation of power to satellites with degraded solar arrays will be a priority service offering.

Achievable power densities at a specified distance are dramatically impacted by increasing beam frequency despite an anticipated fall off in efficiency. Even more striking is the almost an order of magnitude reduction in rectenna area required moving from Ka Band to W Band. Having a validated SSPB testbed will allow the piecewise optimization of the end-to-end system (i.e., reducing and/or allowing the reallocation of power, mass, and volume), as well as allowing for incremental upgrades, and graceful degradation of a modularized system of systems. One of the mission’s goals is to advance the Technological Readiness Level (TRL) of radiant energy beaming technology to the point where it can be deployed in support of one or more missions (i.e., moving from TRL 4 to 8/9).

Currently, the largest customers for power in Cislunar space are the Geosynchronus Communications Satellites (~443 active) with electrical energy demands ranging from ~2 to ~20 kW. As the satellite communication market bifurcates into a new market for large consellations of small satellites to serve acceptance level customers (Quality of Service (QoS) provided is what can be delivered) and a maturing QoS driven market which is evolving to larger and increasingly immortal platforms with plug-in/plug-out technology and rapidly increasing electrical energy demands.

The rate of improvement in transponder technology means that satellites with a 15 year design lift are now obsolete after about 8 years, because the new satellites have such dramatically greater bandwidth. The industry wants a satellite that lasts half as long and costs half a much, which cannot be achieved by simply scaling the size of the satellite.

The XISP-Inc proposed cubesat target demonstrating power beaming from ISS will require the cooperation of several elements of NASA and Industry, but would result in near term demonstration of space-to-space power beaming, and allow rapid iteration of designs and experiments.

Establishing a functioning ISS power beaming testbed could allow experimentation and validation of components of larger power beaming systems, and reduce the risk of the development of the larger dedicated systems

Although the experiments with ISS and cubesats would be small scale, there could be immediate applications for subsatellites near ISS, as well as designs for distributed payloads and sensors for deep space missions including lunar and asteroidal assay work.

A primary mission of XISP-Inc is to develop cooperative arrangements with different parts of NASA and different industry partners. The early implementation of a power beam demonstration on ISS, coordinated by XISP-Inc, could enhance and enable the demonstration of other power beaming designs.

There is no technology currently available that can allow separation of solar arrays from other spacecraft systems (e.g. the sensor package, pointing/mobility systems, communication equipment). State of the art beamed power systems are at TRL 4. The proposed demonstration will be the first ever commercial system test of in-space beamed power, advancing this technology to TRL 8/9.

The primary innovations are:

- the physical separation of electricity generation from point-of-use
- the ability to characterize and optimize high frequency (Ka, W, and optical) power transfer
- SSPB in a safe and efficient manner (beaming control and safety interlock system)
- Power/Data/Communications/Navigation/Time Multiplexing
- Power and allied utility waveforms for Software Defined Radios (SDR)
- Converged Radio Frequency & Optical SDR electronics
- Bi-modal green propellant (Water based and electric thrusters for propulsion and active attitude control systems)

SSPB is enabling for missions intended to operate in dusty and shadow environments, such as asteroid or planetary surface activities and dark lunar craters, as well as disaggregated systems in Earth orbit. This Investigation will establish a testbed on the ISS that will be used to verify the unique benefits of Space-to-Space Power Beaming relative to the current state-of-art. These advantages are summarized in Figure 1 - Unique Benefits of Space-to-Space Power Beaming Relative to the Current State-of-Art.

C. What is the Proposed Solution?

In the near term beaming power and ancillary services from the ISS can provide the necessary redundancy/fault tolerance to enable a return to normal ISS operations while one or more spacecraft are co-orbiting with the ISS.

The ability to beam power from one or more dedicated power generation satellites located in an accessible near-by orbit to GEO ComSat spacecraft holds multiple benefits for GEO ComSat operators. The ability to decouple the power generation from the satellite bus allows:

1) Moving power generation equipment from Capital Expenditures (CapEx) to Operating Expenditures (OpEx), from the ComSat perspective. This reduces CapEx for new satellites, shifting the risk profile.

2) Decoupling of the power generation investment from the transponder investment. Power generation to be amortized over the life of several satellites launched in sequence with ever improving transponder technology

3) Decouples the requirements of power generation (sun pointing, staying out of eclipse) from the communications requirements (earth-pointing, stationary on the equator during eclipse season)

4) Provides for economies of scale in the power generation equipment, as one power beaming satellite could be scaled to generate between 100 to 1000 kW with current design options allowing many simultaneous customers to be served.

Space-to-space power beaming is an application of Space Solar Power technology which could be tested/implemented now to immediate benefit as well as serve as a means of incrementally maturing the technology base.

XISP-Inc has brought together a truly innovative partnership of interested parties to accomplish this TD^3 mission including both government, commercial, university, non-profit, and international participants.

This mission starts with the design of a parametric model for unbundled power systems for spacecraft propulsion and/or sustained free flyer/surface operations in conjunction with the NASA ARC Mission Control Technologies Laboratory as well as other interested parties and the subsequent systems engineering of ground and ISS testbed environments. Exercising the testbed produces the data necessarily to characterize, optimize, and write the operational rules for the demonstration of frequency agnostic radiant energy beaming. The opportunity to craft viable technology demonstrations will establish the basis for a confluence of interest between real mission users and the technology development effort. This could lead to a range of TD^3 mission extensions on the ISS and subsequent fight opportunities that can make efficient and effective use of beamed energy for sustained operations as well as for augmented propulsion.

Several potential research opportunities have emerged that could make use of a combination of resources currently available or that can be readily added to ISS:

Of particular interest is the use of one or more of the available Ka band (27 to 40 Ghz) communications transmitters on ISS initially because of minimal safety concerns associated with additional use of already operational systems. The next anticipated step is adding one or more optimized W band transmitters (75 to 110 GHz) as well as higher frequency systems (e.g.eye-safe, laser light in the range of 1.4 microns to 2 microns) based on the operational procedures already proven out by the Ka band operations. The use of simplified delivery to ISS of enhance equipment and/or flight test articles as soft pack cargo from Earth, the Japanese Kibo laboratory airlock to transition flight systems to the EVA environment, the Mobile Servicing Center for ram-starboard deployment positioning with a zenith bias, and simplified deployment mechanisms can serve as a useful first step toward demonstrating an ability of ISS to support co-orbiting free-flyer spacecraft systems. This combination of equipment allows for power transmission, far field/near field effect analysis and management, formation flying/alignment, and various propulsion approaches to be tested and used to the benefit of multiple experiments; as well as provide augmented power, communications, data, navigation/time, as well as some level of attitude control/positioning services to co-orbiting free-flyers and/or other elements (e.g., OrbitalATK Cygnus, NanoRacks Commercial Airlock, MadeInSpace Archinaut, SpaceX Dragon, Sierra Nevada DreamChaser, JAXA HTV-X, etc.). The repurposing of pressurized logistics carriers that have completed their primary missions into crew-tended co-orbiting free-flyers for some number of extended duration micro-g/production manufacturing cell runs is an extraordinarily cost effective means of providing enhanced ISS capabilities on a commercial basis. Additional commercial space applications include mission enhancements such as expansion of operational mission time, and out-bound orbital trajectory insertion propulsion.

Mission type	**System Options, State of the Art**	**Unique Benefit of Beamed Power**
Asteroid / Lunar / Martian surface activities (dust in a "cloud" and also settling on surfaces)	• Electrostatic "wipers" to clear surfaces • Cables to bring power from remote generation • Large batteries • Large solar arrays to accommodate shading losses • Nuclear power	• Beam frequencies penetrates dust, increasing system end-to-end power collection efficiency • Reduced mass and volume of deployed rovers/surface equipment • "Wipers" ineffective against strong dust chemical / physical adhesion, increasing system reliability and reduced maintenance. • Reduced system and logistic complexity, and increased safety relative to nuclear options
Dark craters, crevasses, lava tubes and areas of extended eclipse duration	• Large batteries • Cables connecting to remote power generation site • Operational limits on activity time, power consumption • Radio-isotope heaters	• Lower mass and volume of rovers relative to long-life batteries • Removal of cables increases reliability and improved system safety, while also removing operational constraints. • Minimal operational limits and constraints allow continuous, long-duration operations for increased equipment utilization efficiency • Reduced system and logistic complexity, and increased safety relative to nuclear options
Disaggregated systems in Earth orbit	• Each element carries solar arrays • System design constraints avoid sun- shadowing • Avoid disaggregation by using small numbers of spacecraft	• Receiving rectenna on each element significantly smaller than solar arrays due to higher received power density and greater conversion efficiency, resulting in lower mass and volume of each element, and decreased atmospheric drag in LEO • Lower cost to upgrade the elements with new and/or different sensor and communications capability because the power generation system does not need to be replaced • No sun-shadowing constraints reduces system and logistic complexity • Large numbers of small elements in a disaggregated system provide increased reliability and resilience relative to smaller numbers of larger elements
Sensor platforms with demanding spacecraft dynamics or thermal / structural loads	• Solar arrays • Attitude control systems with sufficient control authority • Thermal stand-offs	• Receiving rectenna significantly smaller, with greater conversion efficiency (reduced mass, volume, inertia, stiffness, and thermal load) than sensor platform solar arrays • Smaller sensor platform attitude control actuators (reduced mass, volume, power requirements) • Simplified thermal and structural design of the sensor platform • Orbit can be optimized to sensor requirements by removing constraint of solar array pointing
Large power consumers in Earth Orbit (e.g. ComSats)	• Carry large PV arrays, currently less than 40kW	• Moving power generation on the ComSat balance sheet from CapEx to OpEx • On the Power Utility balance sheet, amortize investment over the life of many satellites, and many generations of satellites • Decouple ComSat earth-pointing and station keeping requirements from power generation sun pointing and eclipse avoidance requirements • Economies of scale in the power generation equipment, as one power generation satellite can service perhaps 100 ComSats

Figure 1 - Unique Benefits of Space-to-Space Power Beaming vs. the Current State-of-Art

The ISS Space-to-Space Power Beaming demonstration complements the NASA Technology and Science Research Office' ISS Technology Development Plan for Space Power and Energy, specifically in Power Generation. Providing a practical demonstration of a new capability for point-of-use electricity generation, the ISS Space-to-Space Power Beaming demonstration will be the first ever system test of in-space beamed power. Utilizing the ISS platform for this demonstration will establish a cost effective test-bed on the ISS for future development, characterization and verification of more advanced and improved beamed power technologies. The capability to physical separate solar electricity generation from point of use will enable exploration missions not previously possible by reducing constraints imposed by solar arrays: mass, volume, increased sensor system efficiency, reliability and maintenance in a harsh operational environment relative to photovoltaic arrays that comprise the current start of the art.

The advanced Space-to-Space Power Beaming system allows physical separation of electricity generation from point of use. Mission architectures are made possible for distributed payloads and sensors with application in disaggregated systems in Earth orbit and for demanding deep space missions. This is particularly useful for dust and shadow environments where sunlight may be blocked such as asteroid surface activities and dark lunar craters.

Also, mission architectures are enabled for disaggregated spacecraft where portions of the "swarm" may experience shadow, or where large solar arrays are not desirable or feasible on the sensor platform due to spacecraft dynamics or thermal/structural loads.

Achievable power densities at a specified distance are dramatically impacted by increasing beam frequency despite an anticipated fall off in efficiency. Even more striking is the almost an order of magnitude reduction in rectenna area required moving from Ka Band to W Band.

Having a validated Space-to-Space Power Beaming testbed will allow the piecewise optimization of the end-to-end system reducing and/or allowing the reallocation of power, mass, and volume. One of this missions goals is to advance the Technological Readiness Level (TRL) of radiant energy beaming technology to the point where it can be deployed in support of one or more missions (4 to 8/9).

This mission will result in a Space-to-Space power beaming system which can be deployed for operational use by one or more customers co-orbiting with the ISS. The testing performed, data obtained, and analysis completed will provide the basis for implementing scalable Space-to-Space power beaming systems capable of supporting multiple applications.

The innovation with respect to this work includes being the first Space-to-Space radiant energy beaming testbed. This testbed will support the characterization, optimization, and operationalization of a Space Solar Power radiant energy beaming technology. This includes the development of verified by in situ test: near realtime state models of the radiant energy beam components, beam forming characteristics, variation in performance with frequency (Ka Band, W Band, Other higher) and distance (near field, boundary, and far field), end-to-end and piecewise beam efficiency, differential rectenna response, rectenna geometry variation, optimization metrics by application, as well as operational rules for deployment.

The technical rational proposed for unbundling power systems (i.e., the separation of power generation, transmission, distribution, and loads) is that by doing so it is possible to:

1) reduce spacecraft complexity and thereby reduce cost, schedule, and technical risk.
2) reduce mass and/or volume required to accomplish a given mission.
3) reallocate mass and/or volume to enhance or enable missions.
4) impart additional delta-V, indirectly and/or directly, along velocity vectors of choice to enhance or enable missions
5) foster the development of loosely coupled modular structures to enable:
   - multiple spacecraft (e.g., fractionated spacecraft, interferometric groups, swarms)
   - large distributed payload and subsystem infrastructure to simplify the accommodation of multiple plug-in and plug-out interfaces
   - large scale adaptable space structures that minimize conducted thermal and/or structural loads.

Without a TD^3 mission to blaze the path and provide the follow-through it is not clear why any customer commercial or otherwise would take on the additional risk to incorporate radiant energy beaming technology into their baseline design unless they had no other alternative.

Mitigating risks by providing SSPB as a utility can yield more missions and more successful ones. SSPB can foster the development of loosely coupled modular structures by: enabling large scale adaptable space structures, minimizing conducted thermal and/or structural loads

SSPB can facilitate the formation flying of multiple spacecraft by:

a. Enabling interferometric groups, swarms, and redundancy:

i. A small group of cube-sat based nodes could be demonstrated within both close radio and laser range of the ISS as a precursor of such systems sent to and used in Cislunar space.

ii. The fact that these units could “dock” back at the ISS means that these units could be serviced, repaired or returned as part of the test-bed evaluation and evolution process).

iii. Validated units checked out at the ISS could be launched from the ISS to take up Cislunar long duration stations so as flight systems gain maturity the end point of their demonstration is actually commercial / or NASA operational deployment.

b. Creating new data fusion and pattern recognition options. SSPB can simplify distributed payload and subsystem infrastructure by: a. enabling multiple plug-in and plug-out interfaces, and

c. opening new opportunities for shared orbital platforms, including but not limited to: communications, remote sensing, navigation, time, and power.

The implementation of the cubesat based power beaming testbed demonstrating power beaming from ISS requires the cooperation of NASA, ISS International Partners, academia, and industry. If the necessary confluence of interests is established, the results will include the near term demonstration of SSPB which satisfies one or more commercial customer requirements, and allows the rapid iteration of designs and experiments. It is anticipated that establishing a functioning ISS power beaming testbed could allow experimentation and validation of components of larger power beaming systems, and reduce the risk of the development of the larger dedicated systems. This work also serves as a useful first step toward demonstrating the ability of ISS to support co-orbiting free-flyer spacecraft systems. The enhanced testbed could allow repurposing of some ISS cargo delivery vehicles as crew-tended free-flyers for some number of extended duration experiments.

Furthermore, this work can develop into space electrical services as a commercial utility infrastructure. Accordingly, this work reinforces the United States leadership in the global high-tech marketplace as well as providing extraordinary opportunities for international cooperation and collaboration.

This work is part of a set of commercial missions stemming from ongoing technical discussions between NASA Headquarters and XISP-Inc, as well as an in-place NASA ARC Space Act Agreement for Mission Operations Control Applications (MOCA).

It is useful to note that the Space Station solar arrays can also be described in square meters of reception area exposed to 1360 watts of solar flux for each meter (Isc). The actual DC maximum output would be a useful benchmark of this system and in comparison with any hoped for increase of efficiency with technology improvements and in comparison with the scale of any proposed test-bed demonstrator.)

D. Technical Approach

SSPB is an application of Space Solar Power technology which could be tested/implemented now to immediate benefit as well as serve as a means of incrementally maturing the technology base. XISP-Inc has brought together an innovative partnership of interested parties to accomplish technology development work in this area including government, commercial, university, and non-profit sectors. Many formal letters of interest have been submitted to NASA and/or XISP-Inc and are available on request. This mission starts with the design and implement/prototype of a parametric model for unbundled power systems for spacecraft propulsion as well as sustained free flyer/surface operations in conjunction with the NASA ARC Mission Control Technologies Laboratory and other interested parties. This work has provided an opportunity to craft a viable basis for establishing a confluence of interest between real mission users and the TD^3 effort. This could lead to a range of fight opportunities that can make efficient and effective use of beamed energy for propulsion and/or sustained operations. Already, several potential research opportunities have emerged that could make use of a combination of resources currently available or that can be readily added to ISS.

The proposed mission evolution would be:

1) Cubesat testbed/demonstration/deployment at ISS.
2) Commercial co-orbiting free flyer lab testbed/demonstration/deployment at ISS.
3) Commercial power services infrastructure testbed/demonstration/deployment at ISS.

Of particular interest is the use of one or more of the available Ka band (27 to 40 Ghz) communications transmitters on ISS initially because of minimal safety concerns associated with additional use of already operational systems. The next anticipated step is adding one or more optimized W band transmitters (75 to 110 GHz) as well as higher frequency systems (e.g.eye-safe, laser light in the range of 1.4 microns to 2 microns) based on the operational procedures already proven out by the Ka band operations. The use of simplified delivery to ISS of enhance equipment and/or flight test articles as soft pack cargo from Earth, the Japanese Kibo laboratory airlock to transition flight systems to the EVA environment, the Mobile Servicing Center for ram-starboard deployment positioning with a zenith bias, and simplified deployment mechanisms all facilitate demonstrating the ability of ISS to support co-orbiting free-flyer spacecraft systems. This combination of equipment allows for a testbed environment for power transmission, far field/near field effect analysis and management, formation flying/alignment, and various propulsion approaches to be tested and used to the benefit of multiple experiments; as well as provide augmented power, communications, data, navigation/time, as well as some level of attitude control/positioning services to co-orbiting free-flyers and/or other elements (e.g., OrbitalATK Cygnus, NanoRacks Commercial Airlock, MadeInSpace Archinaut, SpaceX Dragon, Sierra Nevada DreamChaser, JAXA HTV-X, etc.). The repurposing of pressurized logistics carriers that have completed their primary missions into crew-tended co-orbiting free-flyers for some number of extended duration micro-g/production manufacturing cell runs is an extraordinarily cost effective means of providing enhanced ISS capabilities on a commercial basis. Additional commercial space applications include mission enhancements such as expansion of operational mission time, and out-bound orbital trajectory insertion propulsion.

E. Objectives and Significance

The overarching objective of this mission is to hasten the development of viable applications of space solar power technology through focused incremental TD^3 efforts. These efforts can serve to bridge the technology development "valley of death" as well as substantially mitigate (perceived and actual) cost, schedule, and technical risk associated with the short, mid, and long term applications of the technology. The potential of space solar power technology has been examined in some detail for decades by William Brown and other researchers providing both a technical foundation and an inspiration to bring this work to fruition. [1-6] This mission will provide a radiant energy beaming testbed environment for technology development, demonstrable beamed services applicable to some number of potential customers, and deployable beamed services for operational use by one or more customers co-orbiting with the International Space Station (ISS).

This proposed work intersects the ISS Technology Demonstration Plan in the following areas:

1) Space Power and Energy –
    - Power Generation by merging reflectarray solar array/Tx/Rx technology with optimized power receiving antenna (rectenna) designs.
    - Energy Transfer by technology development, demonstration and deployment of a characterized, optimized, and operationalized Ka and W band power transmission services in an end-to-end radiant energy beaming system for ISS co-orbiting free-flyers.
2) Communications and Navigation –
    - Integrated Beamed Utility Services by technology development, demonstration and deployment of characterized, optimized, and operationalized interleaved communication and navigation services in an end-to-end radiant energy beaming system for ISS co-orbiting manufacturing cell free-flyer missions, asteroidal assay missions, and lunar surface operations support missions.
    - Plug-In/Plug-Out Systems by technology development, demonstration and deployment of characterized, optimized, and operationalized beamed utility connections for platform instruments.
3) Operational Process and Procedures –
    - Backup Power and Communication Services by technology development, demonstration and deployment of characterized, optimized, and operationalized use of integrated beamed utility services delivered by radiant energy beaming for ISS co-orbiting free-flyers.
4) In-Space Propulsion –
    - Radiant Energy Beam Propulsion Augmentation by technology development, demonstration and deployment of a characterized, optimized, and operationalized of radiant energy beaming system that imparts additional energy as electricity and/or heat to ISS outbound free-flyers.

This proposed work intersects the Commercial Space Utilization Office Thrust Areas in the following ways:

1) The use of the ISS as a Space Solar Power Radiant Energy Beaming technology development testbed, as a technology demonstration platform, and as a deployment platform for mission applications constitutes an innovative use of the ISS and ISS hardware. The work leverage existing capabilities to stimulate both utilization of the ISS and economic development in the U.S.
2) By adding Space Solar Power Radiant Energy Beaming as a testing tool, implementing near realtime state model enhanced mission operations control applications, demonstrating and deploying integrated power/data/communications services that can be mission enhancing if not mission enabling all serve to improve existing ISS capabilities. These enhances will serve to increase efficiency and effectiveness of the technology demonstrations and science investigations performed on the ISS.
3) This commercial mission implements unique partnering arrangements that both leverage NASA's existing capabilities and increase the commercial participation in research and on board services.

F. Benefit to Humankind and Social Impact

The overarching objective of this mission is to hasten the development of viable applications of space solar power technology through focused incremental TD^3 efforts. These efforts can serve to bridge the technology development "valley of death" as well as substantially mitigate (perceived and actual) cost, schedule, and technical risk associated with the short, mid, and long term applications of the technology.

The potential of space solar power technology has been examined in some detail for decades by William Brown and other researchers providing both a technical foundation and an inspiration to bring this work to fruition. This mission will provide a radiant energy beaming testbed environment for technology development, demonstrable beamed services applicable to some number of potential customers, and deployable beamed services for operational use by one or more customers co-orbiting with the International Space Station (ISS).

The near-term benefit of this mission is that it increases the available resources of the ISS National Lab by facilitating and supporting the operation of crew-tended co-orbiting free-flying systems. In the mid-term the Cislunar electrical and allied utilities services will prove invaluable in supporting the growing utility needs of the next generation of Earth- and space-facing applications, satellites, platforms, and facilities. In the long-term Space Solar Power technology may prove instrumental in meeting the both the United States and the world's baseload electrical energy demand in a cost effective, safe, and environmentally benign manner as well as saving lives by rapidly delivering power to disaster areas and other mission critical environments.

G. Feasibility

XISP-Inc received input from NASA JSC Code OZ regarding our January 20, 2017 submittal on the RESEARCH OPPORTUNITIES FOR ISS UTILIZATION NASA Research Announcement: NNJ13ZBG001N Soliciting Proposals for Exploration Technology Demonstration and National Lab Utilization Enhancements stated as follows: "NASA has determined that 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 proposal [proposed mission] is relevant to NASA's exploration goals and reflects the involvement of a team with appropriate experience."

While the project is not yet fully resourced, the XISP-Inc Consortium includes: over 20 companies, over 15 consultants, 3 government agencies, 4 non-profit organizations, and 10 Universities. To date the direct funding for XISP-Inc has been through Barnhard Associates, LLC and EXOS Aerospace and Technologies, Inc. Estimated cash and In-kind investment made by XISP-Inc in the mission development effort is in excess of $1 million Dollars. In any event, the cash and/or in-kind contributions from the XISP-Inc Consortium will be equal to or larger than the NASA and/or CASIS direct contribution. It is anticipated that given an allocation of ISS National Lab resources, commercial cargo space, integration Verification & Validation support, and a modest amount of mission development funding XISP-Inc will be able to raise the remaining funds required through a combination of grant, debt and/or equity financing. XISP-Inc would appreciate any assistance CASIS can provide in identifying additional funding sources/Consortium participants. With the successful accomplishment of the SSPB TD^3 mission it is anticipated that the Consortium will be able to raise the resources required and already has the team of experienced personnel to move forward with the commercialization of the mission (i.e., the Lunar Power & Light Company).

H. STEM Component

XISP-Inc seeks to provide opportunities for constructive engagement of undergraduate and graduate students in academic-schedule-compatible capacity-building research and operations work directly supporting space TD^3 missions. Opportunities are being crafted with a variety of universities to support the integration of enhanced flight test article components, innovative testbed research tracks, as well as experiment operations via virtualized operations centers.

In addition, as a rapidly advancing TD^3 mission, there are multiple opportunities for aspirational and technical STEM teaching moments based on the technical details of the mission as well as the potential applications that can be tailored to K-12 students.

I. Schedule & Budget

The total estimated time to complete the SSPB TD^3 mission as scoped is twenty-four (24) months. The runout budget estimate (both cash and in-kind contributions) for the SSPB TD^3 mission is less than $10 million dollars.

Total implementation costs assume assistance with one (1) 6U cubesat flight test article (~14 kg) using water based thrusters shipped to station as softpack pressurized cargo on a commercial cargo flight and one (1) Exposed Facility payload carrier (less than 500 kg) shipped to the station as unpressurized cargo on a commercial cargo flight.

Known ISS interface issues include:

1) Commercial cargo (pressurized & unpressurized),

2) Kibo Airlock,
3) Kibo Exposed Facility (EF) Payload Interface (power, data, thermal),
4) JEM RMS (if required),
5) Mobile Servicing Centre (MSC) including the Special Purpose Dexterous Manipulator (SPDM),
6) One or more existing ISS Ka band transceivers,
7) Payload data network & laptop,
8) ISS power system (use of 1 to 2 Remote Power Controllers), as well as
9) ISS Attitude Control System & Propulsion.

Additional interface considerations include:

1) use of the NASA Open Mission Control Technologies (MCT) software suite with XISP-Inc provided near real-time state model extensions,
2) optimized Ka band to optical transceivers at EF payload site or alternate location.
3) Wherever possible Interface Verification & Validation (IV&V) based on ground testing and/or similarity to previously flown and/or currently flying equipment will be used.

Total assumes the currently defined scope of the TD^3 mission, not including other technology development investments and resources that are being leveraged to facilitate the mission (i.e., cost of ISS, commercial cargo, NASA facilities/equipment & staff/contractors, International Partner facilities/equipment & staff/contractors, as well as full cost accounting for In-Kind Consortium provided resources).

Total of funds is to be raised and contributed by members of the the Consortium. Current key commercial members of the consortium include: XISP-Inc, Raytheon, OrbitalATK, Made In Space, Satellite Bus & System Vendors (bid out), Immortal Data, Deep Space Industries, NanoRacks, and Tethers Unlimited. The balance of required funds will have to be raised from a combination of grants, NASA Space Act Agreement milestone achievement contracts, equity financing, and debt financing.

Funding has been requested from the ISS National Lab Manager, the Center for Advancement of Science In Space (CASIS) to assist in mission development, and to cover the launch and ISS operations integration costs.

NASA has indicated that FY 2017 direct funding is not available to support this mission via the Human Exploration and Operations Mission Directorate (HEOMD) and status of subsequent year funding remains to be determined. Accordingly, the mission budget assumes a minimum level of NASA direct funding each year as a placeholder for potential direct participation by NASA by either adding additional milestones and/or accelerating milestones along with the commensurate funding for accomplishing the same.

Total of In-Kind contributions will include the indirect XISP-Inc costs, and a minimal accounting for In-Kind investment by the Consortium (e.g., Raytheon has performed a substantial amount of work for the Department of Defense on W band microwave transmitters as well as Internal Research and Development (IRAD) investments in a wide range of microwave research, Barnhard Associates LLC has provided business operations support and mission development funding for XISP-Inc, etc.).

The Lunar Power & Light (LP&L) Company will provide electrical power and allied utilities (communications, data, and navigation/time) to the addressable markets in Cislunar space from the Karman Line (100 km) to the surface of the Moon.

Detailed addressable market summaries (i.e., concept schematic diagram, addressable market size, key considerations/drivers, technology portfolio - buy/build/develop, and cash flow budget/analysis/projection) are being prepared in conjunction with subject matter experts.

We are proving out the business case for Space-to-space power beaming applications as well as retiring cost, schedule, and technical risk for Space-to-alternate surfaces, and Space-to-Earth applications. We will establish the veracity of our hypothesis that there is an economy of scale with respect to space power generation and how to exploit it.

This TD^3 mission will enable ISS co-orbiting crew-tended free-flyer missions as normal ISS operations and blaze a commercial path to serving degraded legacy satellite systems in the near-term, enhanced satellite systems in the mid-term, and “immortal” platform systems in the long-term.

The TD^3 mission development effort has progressed from concept development to the formulation and founding of a commercial electrical utility consortium the Lunar Power & Light (LP&L) Company.

The Consortium will execute the SSPB TD^3 mission as a commercial mission based on public/private partnership & NASA space act agreement authority. The consortium includes commercial, government, university, non-profit, individual, as well as international participants.

The key considerations for a Cislunar electrical utility include:

1) Addressable markets include LEO Karman Line (100 km) through to the lunar surface
2) Customer requirements focused, frequency agnostic

3) Cash Flow Models for serving each addressable market
4) Progression from Emergency ➔ Servicing ➔ Augment ➔ Backup ➔ Primary Power
5) Power Generation/Transmission/Delivery Utility model
6) Overlay with Communications, Data, Navigation, and Time

The Lunar Power & Light (LP&L) Company intends to serve the anticipated 3 to 8 Billion/year market for Geo Comsat power within 10 years and other addressable markets from Karman Line (100 km) up through to the surface of the Moon, starting with real customers from year one.

J. Preparing the Market & Mission Development

From 2005 to the present over 51 related technical papers and/or presentations have been made by Gary Barnhard to a wide range of professional fora related to Space Solar Power, Allied Utilities (communications, data, navigation/time) and Technology Development, Demonstration, and Deployment missions. Papers and presentations are scheduled for AIAA Space 2017, IAC 2017, and IEEE WiSEE 2017.

Potential Customers are being sought in the following addressable markets:

1) Co-orbiting/LEO
2) LEO/MEO/HEO/GEO
3) Libration Point/Trajectory Insertion/Navigation Waypoints
4) Lunar Resonance Ground Tracking Orbit
5) Lunar Surface
6) Asteroidal Surface

XISP-Inc is part of the ULA sponsored Cislunar Marketplace development effort involving over 150 entities.

K. Experiment Objectives

The experiment objectives that we have defined for this work are:

1) Demonstrate Space-to-Space Power Beaming (SSPB) by powering first one then multiple co-orbiting spacecraft initially using ISS based Ka band and W band transmitters.
2) Demonstrate the successful characterization as well as the direct and indirect use of radiant energy “beam” components.
3) Reduce the cost, schedule, and technical risk associated with the use of the space solar power technology to better address the mission challenges for a new spacecraft and/or infrastructure.

The innovation with respect to this work includes being the first Space-to-Space TD^3 radiant energy beaming testbed. This testbed will support the characterization, optimization, and operationalization of a Space Solar Power radiant energy beaming technology. This includes the development of verified by in situ test: near realtime state models of the radiant energy beam components, beam forming characteristics, variation in performance with frequency (Ka Band, W Band, Other higher) and distance (near field, boundary, and far field), end-to-end and piecewise beam efficiency, differential rectenna response, rectenna geometry variation, optimization metrics by application, as well as operational rules for deployment.

L. Technical Rationale

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

1) reduce spacecraft complexity and thereby reduce cost, schedule, and technical risk.
2) reduce mass and/or volume required to accomplish a given mission.
3) reallocate mass and/or volume to enhance or enable missions.
4) impart additional delta-V along velocity vectors of choice to enhance or enable missions
5) foster the development of loosely coupled modular structures to enable: multiple spacecraft (e.g., fractionated spacecraft, interferometric groups, swarms) large distributed payload and subsystem infrastructure to simplify the accommodation of multiple plug-in and plug-out interfaces large scale adaptable space structures that minimize conducted thermal and/or structural loads.

Mitigating risks by providing SSPB as a utility can yield more missions and more successful ones. SSPB can foster the development of loosely coupled modular structures by:

1) enabling large scale adaptable space structures
2) minimizing conducted thermal and/or structural loads.

SSPB can facilitate the formation flying of multiple spacecraft by:

1) Enabling interferometric groups, swarms, and redundancy:

i. A small group of cube-sat based nodes could be demonstrated within both close radio and laser range of the ISS as a precursor of such systems sent to and used in Cislunar space, as well as serving as backup to those systems.

ii. The fact that these units could "dock" back at the ISS means that these units could be serviced, repaired or returned as part of the test-bed evaluation and evolution process).

iii. Validated units checked out at the ISS could be launched from the ISS to take up Cislunar long duration stations so as flight systems gain maturity the end point of their demonstration is actually commercial / or NASA operational deployment.

b. Creating new data fusion and pattern recognition options.

SSPB can simplify distributed payload and subsystem infrastructure by:

1) enabling multiple plug-in and plug-out interfaces, and

2) opening new opportunities for shared orbital platforms, including but not limited to: communications, remote sensing, navigation, and power

M. Demonstration Technical Approach and Methodology

This work begins with a top level view of the subsystems/functional components of a spacecraft electrical power system. There is a need to structure and order the knowledge of what is known, as well as what is known to be unknown in order to make this analysis tractable.

This experiment set will give mission users an enhanced alternate power supply and substantiate further development of power beaming technology. This experiment is an opportunity to craft viable technology demonstrations that will establish the basis for a confluence of interest between real mission users and the technology development effort. The results of this effort will lead to the effective use of beamed energy to support:

1) sustained operations,

2) directly and/or indirectly augmented propulsion,

3) loosely coupled modular structures, and

4) new opportunities for advanced modular infrastructure.

The availability of diverse power source options that can at least provide minimum essential power could prove to be an invaluable resource in contingency situations.

N. SSPB Test Bed Experiments

For the purposes of this work we have defined the SSPB Test Bed Experiments as:

1) Performance Characterization

a. Define energy needed for different applications for power transmission by microwave, field strength determination of losses in transmitters, transmitting antennas, rectennas, power bus losses with different waveforms,

b. Optimize DC voltages needed during mission cubesat experiments, future manufacturing processes, define best choice of DC load voltage in the 3 to 12 volt range to optimize voltage needed minimize conducted and radiated Electromagnetic Interference / Radio Frequency Interference created during mission tests. This is needed to improve signal to noise ratio for receiving data, status, and control. Scale voltage and current to higher levels for other missions for manufacturing, telecommunications, and for large scale data facilities.

c. Define a range of VoltAmps (power) and VoltAmpHours (energy) for future missions for manufacturing. Determine reactive power and energy for future missions for processes with nonlinear loads.

2) End-to-End & Piecewise Efficiency Optimization

a. DC ===> Microwave,

b. Beam Forming, Transmission, Rectenna

c. Microwave ===> DC

3) Far/Near Field Effects & Boundaries

4) Formation Flying/Alignment/Loosely Coupled Structures

5) Optimization/Scaling/Efficacy of the Solution Set

The essential issue is answering the question of "Where does it make sense to use the technology?"

This concept of operations is summarized in Figure 2 – ISS Space-to-Space Power Beaming Mission Diagram.

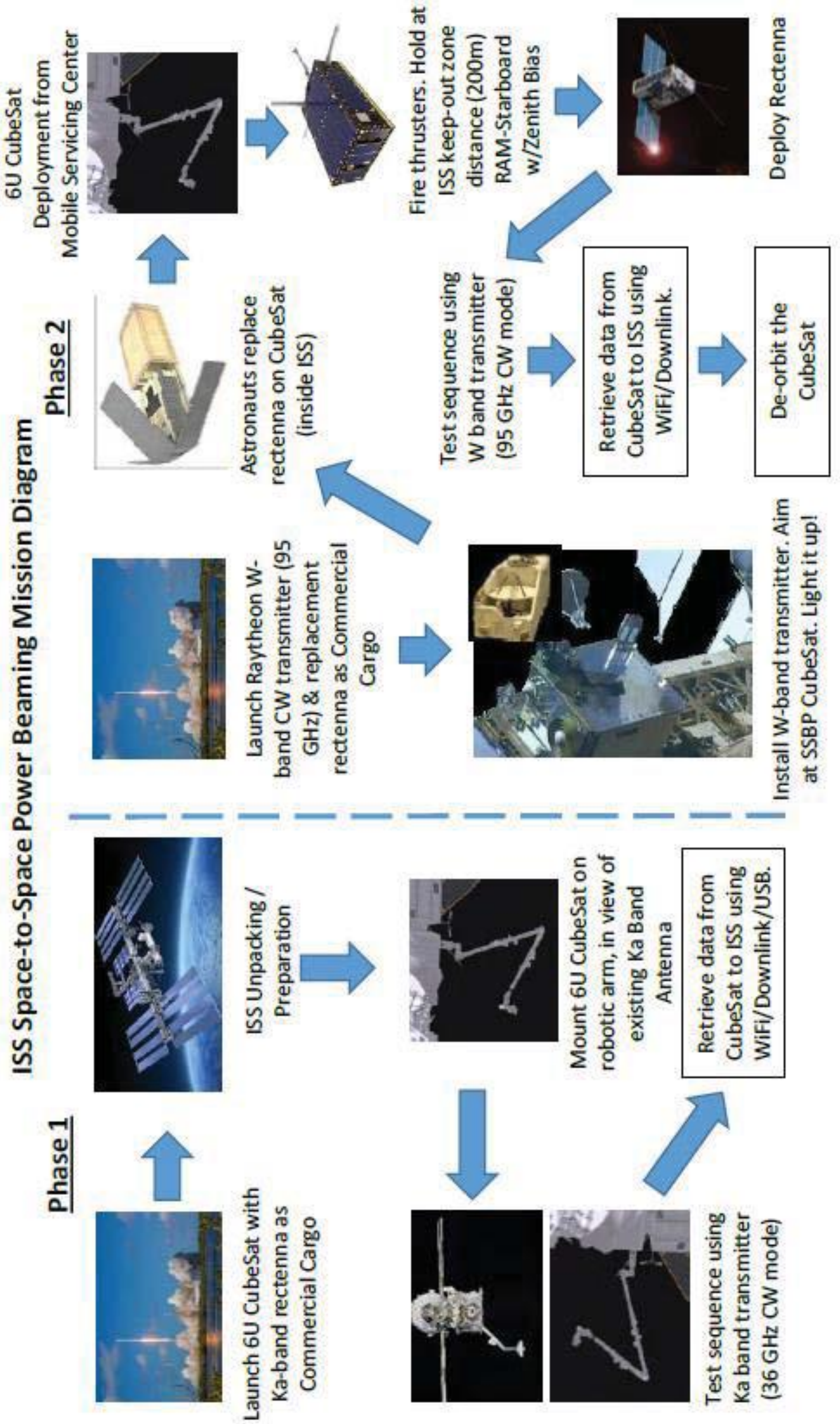


Figure 2. ISS Space-to-Space Power Beaming Mission Diagram.

1) Mitigating risks by providing SSPB as a utility can yield more missions and more successful ones
2) SSPB can foster the development of loosely coupled modular structures by:
    a. enabling large scale adaptable space structures
    b. minimizing conducted thermal and/or structural loads
3) SSPB can facilitate the formation flying of multiple spacecraft by:
    a. enabling interferometric groups, swarms, and redundancy
        i. A small group of cube-sat based nodes could be demonstrated within both close radio and laser range of the ISS as a precursor of such systems sent to Cislunar space.
        ii. The fact that these units could "dock" back at the ISS means that these units could be serviced, repaired or returned as part of the test-bed evaluation and evolution process)
        iii. Validated units checked out at the ISS could be launched from the ISS to take up cislunar long duration stations so as flight system gain maturity the end point of their demonstration is actually commercial/ or NASA operational deployment.
    b. creating new data fusion and pattern recognition options
4) SSPB can simplify distributed payload and subsystem infrastructure by:
    a. enabling multiple plug-in and plug-out interfaces
    b. opening new opportunities for shared orbital platforms
    c. communications
    d. remote sensing
    e. navigation
    f. power

O. Relevance to NASA and Commercial Space Development

This work is part of an overarching Space Act Umbrella Agreement under negotiation between NASA Headquarters and XISP-Inc, for which the Commercial Space-to-Space Power Beaming (SSPB) mission is an Annex, as well as an in-place NASA ARC Space Act Agreement for Mission Operations Control Applications (MOCA).

The XISP-Inc Commercial SSPB mission using cubesat targets to demonstrate power beaming from ISS requires the cooperation of NASA, Industry, academia, and international partners.

It is useful to note that the Space Station solar arrays can also be described in square meters of reception area exposed to 1360 watts of solar flux for each meter (I_{sc}). The actual DC maximum output would be a useful benchmark of this system and in comparison with any hoped for increase of efficiency with technology improvements and in comparison with the scale of any proposed test-bed demonstrator.)

The work will result in a near term demonstration of space-to-space power beaming, and provide a test bed to allow for the rapid iteration of designs and experiments.

Establishing a functioning ISS power beaming testbed could allow experimentation and validation of components of larger power beaming systems, and reduce the risk of the development of the larger dedicated systems

Although the experiments with ISS and cubesats would be small scale, there could be immediate applications for subsatellites near ISS, as well as designs for distributed payloads and sensors for deep space missions including lunar and asteroidal assay work.

A primary mission of XISP-Inc is to develop cooperative arrangements with different parts of NASA and different industry partners. The early implementation of a power beam demonstration on ISS, coordinated by XISP-Inc, could enhance and enable the demonstration of other power beaming designs.

The ISS is an extraordinary resource that can be leveraged to dramatically lower the cost of space solar power technology development, demonstration, and deployment.

P. Mission Concept

Space-to-space power beaming is an application of Space Solar Power technology which could be tested/implemented now to immediate benefit as well as serve as a means of incrementally maturing the technology base.

XISP-Inc has brought together an innovative partnership of interested parties to accomplish technology development work in this area including both government, commercial, university, and non-profit sectors. Many formal letters of interest have been submitted to NASA and/or XISP-Inc and are available on request.

This mission starts with the design and implement/prototype a parametric model for unbundled power systems for spacecraft propulsion as well as sustained free flyer/surface operations in conjunction with the NASA ARC Mission

Control Technologies Laboratory and other interested parties. This work has provided an opportunity to craft a viable basis for establishing a confluence of interest between real mission users and the technology development, demonstration, and deployment effort. This could lead to a range of fight opportunities that can make efficient and effective use of beamed energy for propulsion and/or sustained operations. Already, several potential research opportunities have emerged that could make use of a combination of resources currently available or that can be readily added to ISS.

The proposed mission evolution would be:

1) Cubesat testbed/demonstration/deployment at ISS
2) Commercial co-orbiting free flyer lab testbed/demonstration/deployment at ISS
3) Commercial power services infrastructure testbed/demonstration/deployment at ISS

Of particular interest are the use of:

1) One or more of the available Ka band (27 to 40 Ghz) communications transmitters on ISS,
2) Adding one or more optimized W band transmitters (75 to 110 GHz), a well as
3) Extending the work to higher frequencies up through optical where warranted.
4) The use of simplified delivery to ISS of enhanced equipment and/or flight test articles as soft pack cargo from Earth,
5) The use of the Japanese Kibo laboratory airlock (and/or the planned commercial airlock) to transition flight systems to the EVA environment,
6) The use of the Mobile Servicing Center
7) The use of ram-starboard deployment positioning with a zenith bias, and simplified deployment mechanisms can serve as a useful first step toward demonstrating an ability of ISS to support co-orbiting free flyer spacecraft systems.

This combination of equipment allows for power transmission, far field/near field effect analysis and management, formation flying/alignment, and various propulsion approaches to be tested and used to the benefit of multiple experiments; as well as provide augmented power, communications, and some level of attitude control/positioning services to a co-orbiting free-flyers and/or other elements (e.g., BEAM, Dragon, Cygnus, etc.).

This combination of equipment could be repurposed as crew-tended free-flyers for some number of extended duration micro-g/production manufacturing cell runs.

Also, commercial space applications include mission enhancements, expansion of operational mission time, and out-bound orbital trajectory insertion propulsion.

III. Experiment Outline

This work begins with a top level view of the subsystems/functional components of a spacecraft electrical power system. There is a need to structure and order the knowledge of what is known, as well as what is known to be unknown in order to make this analysis tractable.

A. What are we unbundling?

For the purposes of this work we have defined an end-to-end power system as consisting of:

1) Sources
2) Transducers
3) Storage
4) Transmission/Distribution/Conversion
5) Loads
6) Systems Management
    a. Instrumentation/Sensors
    b. Actuators/Mechanisms/Thermal Sink/Grounding
    c. Command & Control/Flow Logic

B. SSPB Experiment Overlay

For the purposes of this work we overlay our definition of an end-to-end power system with the particular instances and identify the focus:

- - - - - - - - *ISS Infrastructure (by others)* - - - - - - - - - - - - -

1) Primary Source: Solar flux, LEO
2) Transducer: ISS Power System, photovoltaic cells
3) Storage: ISS Power System, batteries

4) Transmission: ISS Power System, PMAD to JEM EF Utility Port

\- - - - - - - - *Mission Focus* - - - - - - - - - - - - - - - -

5) Input Power: 3 to 6 Kw, JEM Exposed Facility Port
6) DC Power to Microwave Conversion
7) Beam Forming Antenna
8) Free Space Transmission
9) Reception Conversion to DC
10) Delivered Power to Spacecraft Power System Bus

\- - - - - - - *Customer Interface (by others)* - - - - - - - - - - - - - -

11) Spacecraft Loads

C. Experiment Objectives

The experiment objectives that we have defined for this work are:

1) Demonstrate space-to-space power beaming by powering first one then multiple co-orbiting spacecraft initially using International Space Station (ISS) based Ka band and W band transmitters.
2) Demonstrate the successful characterization as well as the direct and indirect use of radiant energy "beam" components.
3) Reduce the cost, schedule, and technical risk associated with the use of the space solar power technology to better address the mission challenges for a new spacecraft and/or infrastructure.

D. Experiment Description

This experiment set will give mission users an enhanced alternate power supply and substantiate further development of power beaming technology.

This experiment is an opportunity to craft viable technology demonstrations that will establish the basis for a confluence of interest between real mission users and the technology development effort.

The results of this effort will lead to the effective use of beamed energy to support:

1) sustained operations,
2) directly and/or indirectly augmented propulsion,
3) loosely coupled modular structures, and
4) new opportunities for advanced modular infrastructure.

The availability of diverse power source options that can at least provide minimum essential power could prove to be an invaluable resource in contingency situations.

E. SSPB Test Bed Experiments

For the purposes of this work we have defined the SSPB Test Bed Experiments as:

1) End-to-End & Piecewise Efficiency Optimization
   i. DC ===> Microwave,
   ii. Beam Forming, Transmission, Rectenna
   iii. Microwave ===> DC
2) Performance Characterization
   i. Define energy needed for different applications for power transmission by microwave, field strength determination of losses in transmitters, transmitting antennas, rectennas, power bus losses with different waveforms,
   ii. Optimize dc voltages needed during mission cubesat experiments, future manufacturing processes, define best choice of dc load voltage in the 3 to 12 volt range to optimize voltage needed minimize conducted and radiated emi and rfi created during mission tests. This is needed to improve signal to noise ratio for receiving data, status, and control. Scale voltage and current to higher levels for other missions for manufacturering, telecommunications, and for large scale data facilities.
   iii. Define a range of Voltamps (power) and Voltamps over time (energy) for future missions for manufacturing. Determine reactive power and energy for future missions for processes with nonlinear loads.
3) Far/Near Field Effects & Boundaries
4) Formation Flying/Alignment/Loosely Coupled Structures
5) Optimization/Scaling/Efficacy of the Solution Set

The essential issue is answering the question of "Where does it make sense to use the technology?"

F. SSPB & Commercial Requirements

For the purposes of this work we have the following commercial mission requirements to address:

1) Asteroidal Assay
   a. Co-orbiting motherships with deployable sensors
   b. Cislunar proving ground mission for Space-to-Alternate Surface radiant energy beaming applications
2) ISS Co-orbiting Free-flyers
   a. Micro-g manufacturing cells
3) Propulsion (delta-V augmentation)
   a. Out bound & cycling spacecraft
   b. Orbital debris management
4) Plug-In/Plug-Out Infrastructure Platforms
   a. Communications, Navigation, Power, etc.
   b. Earth facing, space operations, and space exploration
      i. Emergency Preparedness and Response Networks
      ii. Cislunar infrastructure and adhoc communications & navigation mesh networks
5) Operational Cadence/Cycle Evolution
   a. International Lunar Decade Support

G. Mathematics of Power Beaming

For the purposes of understanding the mathematics of power beaming at an application level there are four schematic elements that must be addressed[1].

1) DC to Microwave Conversion (70-90% efficient, circa 1992) {current estimate is ~95% depending on voltage multiplier ratio}
2) Beam Forming Antenna (70-97% efficient, circa 1992) {current estimate is comparable}
3) Free Space Transmission (5-95% efficient, circa 1992) {current estimate is comparable}
4) Reception Conversion to DC (85-92% efficient, circa 1992) {current estimate is ~95% depending on voltage multiplier ratio}

The theoretical maximum possible DC to DC Efficiency was estimated to be ~76%, circa 1992{use of one cycle modulation could increase this to between 85-95%, not pulse width modulation (pwm)}. The experimental DC to DC efficiency established was ~54%, circa 1992 {this is open area of research where significant increase is anticipated}. While the higher component efficiency values shown above are well established for low frequency microwaves (< 6 GHz) this is not the case for higher frequencies. Recent data suggests for high frequencies the range estimates should be adjusted to:

1) DC to Microwave Conversion (10%-60% efficient, circa 2016)
2) Beam Forming Antenna (50%-80% efficient, circa 2016 assuming the use of reflectors)
3) Free Space Transmission (1%-90% efficient, circa 2016)
4) Reception Conversion to DC (37%-72% efficient, circa 2016) [1-6, 25]

The DC to Microwave Conversion and the Beam Forming Antenna efficiencies have very high observed values that have just improved with time over the values cited and will be a given for the existing ISS transmitters and therefore have been neglected to simplify the initial analysis. However, they will need to be addressed in the development of any optimized radiant energy beam transmitter.

The greatest efficiency variability is with Free Space Transmission. For applications where the receiving antenna (rectenna) size is limited and there is a need to calculate the illuminating power density, p_d, equation (1) can be used[1].

$$P_d = (A_t)(P_t) / (\lambda)^2(D)^2 \tag{1}$$

P_d is the power density at the center of the receiving location [W/cm^2]
P_t is the total radiated power from the transmitter [W]
A_t is the total area of the transmitting antenna [cm^2]
λ is the wavelength [cm]
D is the separation between the transmitting and receiving apertures [cm]

The area of ISS Space Communication and Navigation (SCaN) Test Bed (STB) Ka Band Transmitter Dish ~1642 cm^2 is a placeholder value for available ISS transmitters and is assumed to be the minimum size for an ISS W transmitter phased array plate.

The maximum area of the proposed ISS W Band transmitter phased array plate is 10000 cm^2.

The JEM Exposed Facility (EF) Utility Port input power is 3000 W maximum using one ISS remote power controller module, and 6000 W maximum using two ISS remote power controllers, subject to input power availability.

The ISS spherical zone of exclusion is a 200 m radius extending from the ISS center of mass.

The P_d test cases that have been calculated so far include:

Case 1: Ka Band Low 26.5 GHz,

$D = 200$ m, $A_r = 100$ cm^2 to 10000 cm^2, $\lambda = 1.13$ cm, $A_t = 1642$ cm^2, $P_t = 3000$ W
$D = 200$ m, $A_r = 100$ cm^2 to 10000 cm^2, $\lambda = 1.13$ cm, $A_t = 1642$ cm^2, $P_t = 6000$ W
$D = 200$ m, $A_r = 100$ cm^2 to 10000 cm^2, $\lambda = 1.13$ cm, $A_t = 10000$ cm^2, $P_t = 3000$ W
$D = 200$ m, $A_r = 100$ cm^2 to 10000 cm^2, $\lambda = 1.13$ cm, $A_t = 10000$ cm^2, $P_t = 6000$ W

Case 2: Ka Band Target 36 GHz,

$D = 200$ m, $A_r = 100$ cm^2 to 10000 cm^2, $\lambda = 0.833$ cm, $A_t = 1642$ cm^2, $P_t = 3000$ W
$D = 200$ m, $A_r = 100$ cm^2 to 10000 cm^2, $\lambda = 0.833$ cm, $A_t = 1642$ cm^2, $P_t = 6000$ W
$D = 200$ m, $A_r = 100$ cm^2 to 10000 cm^2, $\lambda = 0.833$ cm, $A_t = 10000$ cm^2, $P_t = 3000$ W
$D = 200$ m, $A_r = 100$ cm^2 to 10000 cm^2, $\lambda = 0.833$ cm, $A_t = 10000$ cm^2, $P_t = 6000$ W

Case 3: W Band Target 95 GHz,

$D = 200$ m, $A_r = 100$ cm^2 to 10000 cm^2, $\lambda = 0.316$ cm, $A_t = 1642$ cm^2, $P_t = 3000$ W
$D = 200$ m, $A_r = 100$ cm^2 to 10000 cm^2, $\lambda = 0.316$ cm, $A_t = 1642$ cm^2, $P_t = 6000$ W
$D = 200$ m, $A_r = 100$ cm^2 to 10000 cm^2, $\lambda = 0.316$ cm, $A_t = 10000$ cm^2, $P_t = 3000$ W
$D = 200$ m, $A_r = 100$ cm^2 to 10000 cm^2, $\lambda = 0.316$ cm, $A_t = 10000$ cm^2, $P_t = 6000$ W

Reception conversion to DC have very high observed values that have improved with time over the values cited and therefore have been neglected to simplify the initial analysis. However, it will need to be addressed in the development of any optimized radiant energy beam rectenna with relative development risk increasing with frequency of the radiant energy beam. In cases where the rectenna aperture is not small in proportion to the transmitter aperture, transmitter power levels are high, and the frequency is high, power received (P_r) calculations break down using the far-field equations. Accordingly, the P_r is calculated using the collection efficiency method[25] shown in equations (2) and (3) as well as Figure 1 - Power Transmission Efficency[25] instead of the far-field equations.

$$P_r = (\zeta)\,(P_t) \qquad (2)$$

where
P_r is the power received at the rectenna [W]
P_t is the total radiated power from the transmitter [W]
ζ is relates the physical parameters of the power beaming system to the collection efficiency

$$\zeta = (D)(W) / (\lambda)(R) \qquad (3)$$

where
ζ "zeta" is the dimensionless value which relates the physical parameters of the power beaming system to the collection efficiency [25]
W is the diameter the area of an equivalent square rectenna which equals $(2)(A_r/\pi)^{1/2}$ [cm]
D is the diameter the area of an equivalent square transmitter antenna which equals $(2)(A_t/\pi)^{1/2}$ [cm]
A_r is the total area of the rectenna [cm^2]
A_t is the total area of the transmitter antenna [cm^2]
λ is the wavelength [cm]
R is the separation between the transmitting and receiving apertures [cm]

The rectenna efficiencies are based of the peak incident power density at the rectenna's center and assumed to be constant across the rectenna area (a reasonable approximation for small rectenna sizes). For the test cases 1, 2, and 3 P_r has been calculated for rectenna sizes ranging from 100 cm^2 to 10000 cm^2 and are shown in following tables:

- Table 1. Power Received for Various Rectenna Sizes with D=200 m, Pt= 3000 W and At = 1642 cm^2
- Table 2. Power Received for Various Rectenna Sizes with D=200 m, Pt= 6000 W and At = 1642 cm^2
- Table 3. Power Received for Various Rectenna Sizes with D=200 m, Pt= 3000 W and At = 10000 cm^2
- Table 4. Power Received for Various Rectenna Sizes with D=200 m, Pt= 6000 W and At = 10000 cm^2

CASE 1 - Space Station Ka Band Transmitter Anticipated Power Received for various rectenna areas - Ka Low 26.5 GHz						
Distance (meters)	Rectenna Area (cm^2)	Wavelength (cm)	Transmitter Area (cm^2)	Power Transmitted (Watts)	Power Density (Watts/cm^2)	Power Received (Watts)
D	Ar	λ	At	Pt	Pd	Pr
200	**100**	1.13	1642	3000	0.009643	**0.95**
200	**200**	1.13	1642	3000	0.009643	**1.96**
200	**300**	1.13	1642	3000	0.009643	**2.96**
200	**400**	1.13	1642	3000	0.009643	**3.91**
200	**500**	1.13	1642	3000	0.009643	**4.75**
200	**600**	1.13	1642	3000	0.009643	**5.76**
200	**700**	1.13	1642	3000	0.009643	**6.76**
200	**800**	1.13	1642	3000	0.009643	**7.74**
200	**900**	1.13	1642	3000	0.009643	**8.75**
200	**1000**	1.13	1642	3000	0.009643	**9.72**
200	**2000**	1.13	1642	3000	0.009643	**19.31**
200	**3000**	1.13	1642	3000	0.009643	**28.49**
200	**4000**	1.13	1642	3000	0.009643	**38.67**
200	**5000**	1.13	1642	3000	0.009643	**48.84**
200	**6000**	1.13	1642	3000	0.009643	**56.26**
200	**7000**	1.13	1642	3000	0.009643	**67.04**
200	**8000**	1.13	1642	3000	0.009643	**75.82**
200	**9000**	1.13	1642	3000	0.009643	**86.42**
200	**10000**	1.13	1642	3000	0.009643	**95.60**

CASE 2 - Space Station Ka Band Transmitter Anticipated Power Received for various rectenna areas - Ka 36 GHz						
Distance (meters)	Rectenna Area (cm^2)	Wavelength (cm)	Transmitter Area (cm^2)	Power Transmitted (Watts)	Power Density (watts/cm**2)	Power Received (Watts)
D	Ar	λ	At	Pt	Pd	Pr
200 m	**100**	0.833	1642	3000	0.017745	**1.80**
200 m	**200**	0.833	1642	3000	0.017745	**3.62**
200 m	**300**	0.833	1642	3000	0.017745	**5.31**
200 m	**400**	0.833	1642	3000	0.017745	**7.14**
200 m	**500**	0.833	1642	3000	0.017745	**8.98**
200 m	**600**	0.833	1642	3000	0.017745	**10.68**
200 m	**700**	0.833	1642	3000	0.017745	**12.35**
200 m	**800**	0.833	1642	3000	0.017745	**14.16**
200 m	**900**	0.833	1642	3000	0.017745	**16.00**
200 m	**1000**	0.833	1642	3000	0.017745	**17.84**
200 m	**2000**	0.833	1642	3000	0.017745	**36.23**
200 m	**3000**	0.833	1642	3000	0.017745	**52.14**
200 m	**4000**	0.833	1642	3000	0.017745	**68.97**
200 m	**5000**	0.833	1642	3000	0.017745	**88.53**
200 m	**6000**	0.833	1642	3000	0.017745	**105.82**
200 m	**7000**	0.833	1642	3000	0.017745	**121.44**
200 m	**8000**	0.833	1642	3000	0.017745	**139.55**
200 m	**9000**	0.833	1642	3000	0.017745	**154.99**
200 m	**10000**	0.833	1642	3000	0.017745	**172.43**

CASE 3 - Optimized W Band Transmitter Anticipated Power Received for various rectenna areas W Target 95 GHz						
Distance (meters)	Rectenna Area (cm^2)	Wavelength (cm)	Transmitter Area (cm^2)	Power Transmitted (Watts)	Power Density (watts/cm**2)	Power Received (Watts)
D	Ar	λ	At	Pt	Pd	Pr
200 m	**100**	0.316	1642	3000	0.123307	**7.69**
200 m	**200**	0.316	1642	3000	0.123307	**15.39**
200 m	**300**	0.316	1642	3000	0.123307	**23.49**
200 m	**400**	0.316	1642	3000	0.123307	**31.09**
200 m	**500**	0.316	1642	3000	0.123307	**38.51**
200 m	**600**	0.316	1642	3000	0.123307	**45.45**
200 m	**700**	0.316	1642	3000	0.123307	**54.06**
200 m	**800**	0.316	1642	3000	0.123307	**61.53**
200 m	**900**	0.316	1642	3000	0.123307	**69.05**
200 m	**1000**	0.316	1642	3000	0.123307	**75.63**
200 m	**2000**	0.316	1642	3000	0.123307	**149.31**
200 m	**3000**	0.316	1642	3000	0.123307	**218.30**
200 m	**4000**	0.316	1642	3000	0.123307	**284.43**
200 m	**5000**	0.316	1642	3000	0.123307	**349.22**
200 m	**6000**	0.316	1642	3000	0.123307	**410.82**
200 m	**7000**	0.316	1642	3000	0.123307	**469.52**
200 m	**8000**	0.316	1642	3000	0.123307	**524.87**
200 m	**9000**	0.316	1642	3000	0.123307	**580.65**
200 m	**10000**	0.316	1642	3000	0.123307	**630.86**

Table 1. Power Received for Various Rectenna Sizes with D=200 m, P_t= 3000 W and A_t = 1642 cm^2

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

Distance (meters)	Rectenna Area (cm^2)	Wavelength (cm)	Transmitter Area (cm^2)	Power Transmitted (Watts)	Power Density (Watts/cm^2)	Power Received (Watts)
D	**Ar**	**λ**	**At**	**Pt**	**Pd**	**Pr**
200	**100**	1.13	1642	6000	0.019286	**1.90**
200	**200**	1.13	1642	6000	0.019286	**3.92**
200	**300**	1.13	1642	6000	0.019286	**5.92**
200	**400**	1.13	1642	6000	0.019286	**7.81**
200	**500**	1.13	1642	6000	0.019286	**9.51**
200	**600**	1.13	1642	6000	0.019286	**11.53**
200	**700**	1.13	1642	6000	0.019286	**13.52**
200	**800**	1.13	1642	6000	0.019286	**15.48**
200	**900**	1.13	1642	6000	0.019286	**17.51**
200	**1000**	1.13	1642	6000	0.019286	**19.45**
200	**2000**	1.13	1642	6000	0.019286	**38.63**
200	**3000**	1.13	1642	6000	0.019286	**56.99**
200	**4000**	1.13	1642	6000	0.019286	**77.33**
200	**5000**	1.13	1642	6000	0.019286	**97.68**
200	**6000**	1.13	1642	6000	0.019286	**112.51**
200	**7000**	1.13	1642	6000	0.019286	**134.09**
200	**8000**	1.13	1642	6000	0.019286	**151.64**
200	**9000**	1.13	1642	6000	0.019286	**172.85**
200	**10000**	1.13	1642	6000	0.019286	**191.19**

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

Distance (meters)	Rectenna Area (cm^2)	Wavelength (cm)	Transmitter Area (cm^2)	Power Transmitted (Watts)	Power Density (watts/cm**2)	Power Received (Watts)
D	**Ar**	**λ**	**At**	**Pt**	**Pd**	**Pr**
200 m	**100**	0.833	1642	6000	0.035490	**3.60**
200 m	**200**	0.833	1642	6000	0.035490	**7.24**
200 m	**300**	0.833	1642	6000	0.035490	**10.61**
200 m	**400**	0.833	1642	6000	0.035490	**14.28**
200 m	**500**	0.833	1642	6000	0.035490	**17.96**
200 m	**600**	0.833	1642	6000	0.035490	**21.36**
200 m	**700**	0.833	1642	6000	0.035490	**24.70**
200 m	**800**	0.833	1642	6000	0.035490	**28.33**
200 m	**900**	0.833	1642	6000	0.035490	**32.00**
200 m	**1000**	0.833	1642	6000	0.035490	**35.68**
200 m	**2000**	0.833	1642	6000	0.035490	**72.46**
200 m	**3000**	0.833	1642	6000	0.035490	**104.29**
200 m	**4000**	0.833	1642	6000	0.035490	**137.94**
200 m	**5000**	0.833	1642	6000	0.035490	**177.07**
200 m	**6000**	0.833	1642	6000	0.035490	**211.63**
200 m	**7000**	0.833	1642	6000	0.035490	**242.88**
200 m	**8000**	0.833	1642	6000	0.035490	**279.11**
200 m	**9000**	0.833	1642	6000	0.035490	**309.98**
200 m	**10000**	0.833	1642	6000	0.035490	**344.85**

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

Distance (meters)	Rectenna Area (cm^2)	Wavelength (cm)	Transmitter Area (cm^2)	Power Transmitted (Watts)	Power Density (watts/cm**2)	Power Received (Watts)
D	**Ar**	**λ**	**At**	**Pt**	**Pd**	**Pr**
200 m	**100**	0.316	1642	6000	0.246615	**24.56**
200 m	**200**	0.316	1642	6000	0.246615	**49.18**
200 m	**300**	0.316	1642	6000	0.246615	**75.08**
200 m	**400**	0.316	1642	6000	0.246615	**99.37**
200 m	**500**	0.316	1642	6000	0.246615	**123.07**
200 m	**600**	0.316	1642	6000	0.246615	**145.26**
200 m	**700**	0.316	1642	6000	0.246615	**172.77**
200 m	**800**	0.316	1642	6000	0.246615	**196.65**
200 m	**900**	0.316	1642	6000	0.246615	**220.70**
200 m	**1000**	0.316	1642	6000	0.246615	**241.72**
200 m	**2000**	0.316	1642	6000	0.246615	**477.21**
200 m	**3000**	0.316	1642	6000	0.246615	**697.70**
200 m	**4000**	0.316	1642	6000	0.246615	**909.03**
200 m	**5000**	0.316	1642	6000	0.246615	**1116.11**
200 m	**6000**	0.316	1642	6000	0.246615	**1312.99**
200 m	**7000**	0.316	1642	6000	0.246615	**1500.60**
200 m	**8000**	0.316	1642	6000	0.246615	**1677.49**
200 m	**9000**	0.316	1642	6000	0.246615	**1855.77**
200 m	**10000**	0.316	1642	6000	0.246615	**2016.25**

Table 2. Power Received for Various Rectenna Sizes with D=200 m, P_t= 6000 W and A_t = 1642 cm^2

CASE 1 - Space Station Ka Band Transmitter Anticipated Power Received for various rectenna areas - Ka Low 26.5 GHz						
Distance (meters)	Rectenna Area (cm^2)	Wavelength (cm)	Transmitter Area (cm^2)	Power Transmitted (Watts)	Power Density (Watts/cm^2)	Power Received (Watts)
D	Ar	λ	At	Pt	Pd	Pr
200	**100**	1.13	10000	3000	0.058736	**5.85**
200	**200**	1.13	10000	3000	0.058736	**11.62**
200	**300**	1.13	10000	3000	0.058736	**17.66**
200	**400**	1.13	10000	3000	0.058736	**23.28**
200	**500**	1.13	10000	3000	0.058736	**28.77**
200	**600**	1.13	10000	3000	0.058736	**35.88**
200	**700**	1.13	10000	3000	0.058736	**40.67**
200	**800**	1.13	10000	3000	0.058736	**48.06**
200	**900**	1.13	10000	3000	0.058736	**51.78**
200	**1000**	1.13	10000	3000	0.058736	**57.39**
200	**2000**	1.13	10000	3000	0.058736	**115.25**
200	**3000**	1.13	10000	3000	0.058736	**170.43**
200	**4000**	1.13	10000	3000	0.058736	**226.16**
200	**5000**	1.13	10000	3000	0.058736	**278.89**
200	**6000**	1.13	10000	3000	0.058736	**331.15**
200	**7000**	1.13	10000	3000	0.058736	**383.69**
200	**8000**	1.13	10000	3000	0.058736	**434.70**
200	**9000**	1.13	10000	3000	0.058736	**482.33**
200	**10000**	1.13	10000	3000	0.058736	**532.15**

CASE 2 - Space Station Ka Band Transmitter Anticipated Power Received for various rectenna areas - Ka 36 GHz						
Distance (meters)	Rectenna Area (cm^2)	Wavelength (cm)	Transmitter Area (cm^2)	Power Transmitted (Watts)	Power Density (watts/cm**2)	Power Received (Watts)
D	Ar	λ	At	Pt	Pd	Pr
200	**100**	0.833	10000	3000	0.108086	**10.83**
200	**200**	0.833	10000	3000	0.108086	**21.46**
200	**300**	0.833	10000	3000	0.108086	**31.81**
200	**400**	0.833	10000	3000	0.108086	**42.77**
200	**500**	0.833	10000	3000	0.108086	**52.69**
200	**600**	0.833	10000	3000	0.108086	**65.36**
200	**700**	0.833	10000	3000	0.108086	**74.37**
200	**800**	0.833	10000	3000	0.108086	**86.34**
200	**900**	0.833	10000	3000	0.108086	**96.72**
200	**1000**	0.833	10000	3000	0.108086	**107.35**
200	**2000**	0.833	10000	3000	0.108086	**209.12**
200	**3000**	0.833	10000	3000	0.108086	**307.35**
200	**4000**	0.833	10000	3000	0.108086	**402.42**
200	**5000**	0.833	10000	3000	0.108086	**493.82**
200	**6000**	0.833	10000	3000	0.108086	**581.84**
200	**7000**	0.833	10000	3000	0.108086	**667.88**
200	**8000**	0.833	10000	3000	0.108086	**749.93**
200	**9000**	0.833	10000	3000	0.108086	**829.86**
200	**10000**	0.833	10000	3000	0.108086	**904.44**

CASE 3 - Optimized W Band Transmitter Anticipated Power Received for various rectenna areas W Target 95 GHz						
Distance (meters)	Rectenna Area (cm^2)	Wavelength (cm)	Transmitter Area (cm^2)	Power Transmitted (Watts)	Power Density (watts/cm**2)	Power Received (Watts)
D	Ar	λ	At	Pt	Pd	Pr
200	**100**	0.316	10000	3000	0.751082	**73.92**
200	**200**	0.316	10000	3000	0.751082	**145.97**
200	**300**	0.316	10000	3000	0.751082	**217.82**
200	**400**	0.316	10000	3000	0.751082	**287.21**
200	**500**	0.316	10000	3000	0.751082	**354.59**
200	**600**	0.316	10000	3000	0.751082	**418.97**
200	**700**	0.316	10000	3000	0.751082	**482.13**
200	**800**	0.316	10000	3000	0.751082	**546.59**
200	**900**	0.316	10000	3000	0.751082	**607.21**
200	**1000**	0.316	10000	3000	0.751082	**664.77**
200	**2000**	0.316	10000	3000	0.751082	**1176.29**
200	**3000**	0.316	10000	3000	0.751082	**1562.24**
200	**4000**	0.316	10000	3000	0.751082	**1850.47**
200	**5000**	0.316	10000	3000	0.751082	**2064.54**
200	**6000**	0.316	10000	3000	0.751082	**2220.75**
200	**7000**	0.316	10000	3000	0.751082	**2329.80**
200	**8000**	0.316	10000	3000	0.751082	**2400.27**
200	**9000**	0.316	10000	3000	0.751082	**2448.70**
200	**10000**	0.316	10000	3000	0.751082	**2481.83**

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

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

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

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

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

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

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

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

The use of Ka Band frequencies are anticipated to prove advantageous for near term orbital testbed purposes based on the availability of transmitters already on orbit as well as terrestrial commercial-off-the-shelf. Any use of Ka Band frequencies for radiant energy beaming must necessarily be carefully coordinated with on going use of the equipment to meet ISS communications requirements. One of the trade study objectives is determine the value of increasing the radiant beam frequency for various applications.

It is useful to note as shown in Table 5 -- Comparing Beaming Power Density and the Solar Constant, I_{sc} = Solar Constant at 1 AU = 0.1367 W/cm^2 is approximately an order of magnitude less than p_d for Case 3 Table 4: W Band Target 95 GHz p_d with $P_t = 6000$ W and A_t = 10000 cm^2. While the calculated values show real promise more rigorous analysis and testing to identify, better characterize, and optimize the efficiency of all elements of end-to-end radiant energy beaming systems is required. Furthermore, the projected conversion efficiency from microwave to DC power (e.g., 85-92% efficient, circa 1992) is significantly greater than the efficiency of even the most advanced solar photovoltaic cells (e.g., less than 46.0%) Accordingly, from the assessments and calculations done to date it can be deduced that there is a reasonable to high likelihood given an optimized radiant energy beam transmitter that there is significant margin in the application trade space for space-to-space power beaming to warrant being considered as a mission enhancing if not mission enabling resource.

	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

One example worth examining is how the possible extension of the useful mission life of proposed NASA Resource Prospector mission from 14 days through a succession of lunar day night cycles would amplify its economic and scientific value. This could be a specific objective of a trade study to determine if Resource Prospector (or an evolved successor) with the potential of providing long duration assays of the lunar surface region are practical and cost effective means of buying down the investment risk of lunar volatiles mining. Understanding the engineering requirements of both the ground unit as well as an orbiting satellite transmitter would move the conversation about cost feasible applications forward.

H. Technology Development

For the purposes of this work we have defined the scope of the technology development involved to include:

1) Knowledge Base on Radiant Energy Beaming
    a. Significant Actors/Interested Entities
    b. Intellectual Commons
    c. Prior Art
        i. Patents & Patents Pending
        ii. Trade Secrets
    d. Known Unknowns
2) End-to-End State Models
    a. Unbundled Electrical Power System
        i. Characterize the radiant energy beam in a near realtime state model

        ii. Optimize the radiant energy beam for performance based on application
        iii. Operationalize the radiant energy beam by defining and encoding the performance envelope and operating rules.
    b. Spacecraft Systems-of-Systems
        i. Mission operations control
3) Beam Sources
    a. Frequency Optimization
        i. 26.5 GHz (Ka Band Low)
        ii. 36 GHz (Ka Band Target)
        iii. 95 GHz (W Band Target)
        iv. Higher Frequencies up through Optical
    b. Power levels
    c. Human effects
    d. Electomagnetic effects
4) Rectennas
    a. Rectenna Areas
        i. 100 cm^2 (1 U) to 1 m^2 (100 U)
    b. Rectenna Types
        i. 2D Rectangular, Polarized Spiral, Fractal, etc.
        ii. 3D Pyramid, Conical, Fractal, etc.
        iii. Reflectarray and photovoltaic combinations
    c. Build Options
        i. Earth manufactured, deployed on-orbit
        ii. Earth manufactured, assembled on-orbit
        iii. 3D Printed on-orbit
5) Flight Test Articles
    a. DSI (3U) Spacecraft
    b. Alpha CubeSat (6U) Spacecraft
6) Flight Support Equipment
    a. Trajectory Insertion Bus
    b. Spacecraft Deployment Flight Support Equipment
    c. Spacecraft Recovery Flight Support Equipment

I. Technology Demonstration

For the purposes of this work we have defined the scope of the technology demonstation involved to include:

1) Radiant Energy Beam Management
    a. Characterization of the radiant energy beam
    b. Optimization of the radiant energy beam
    c. Operationalize the radiant energy beam
2) Test Beds
    a. Near Field/Far Field Test Bed
    b. Loosely Coupled Modular Structures Test Bed
    c. Propulsion Augment Test Bed
    d. Platform Infrastructure Technology Test Bed
3) Rectennas
    a. Differentiation and performance characterization by size
    b. Differentiation and performance characterization by type
    c. Differentiation and performance characterization by build method
4) Flight Test Article & Flight Support Equipment Interfaces
    a. Modular Small Space Craft (e.g., DSI (3U), Alpha CubeSat (6U), etc.) Interfaces
    b. Trajectory Insertion Bus Interfaces
    c. Spacecraft Deployment Interfaces
    d. Spacecraft Recovery Interfaces
    e. Logistics Carrier Augmentation Interfaces

J. Technology Deployment

For the purposes of this work we have defined the scope of the technology deployment involved to include:

1) Asteroidal Assay Mission – The mission objective is to support landed and/or near surface grazing orbiting sensors for asteroid assay work that can be powered by a radiant energy beam from some number of co-orbiting motherships.
2) Co-orbiting Manufacturing Cell Mission – The mission objective is to support the use of one or more ISS logistics carriers as crew tended co-orbiting free flyers for some number of cycles to accommodate manufacturing cells which require more stringent microgravity and/or safety considerations.
3) Beyond Earth Orbit Deployment Platform – The mission objective is to support the use of one or more ISS trajectory insertion bus by directly or indirectly providing a propulsion augment using a radiant energy beam from the ISS.

K. Tetrahedral Target & Formation

For the purposes of this work we have selected a tetrahedral target formation based on the following rationale:

1) A tetrahedron is the most fundamental locked 3 dimensional structure.
2) A tetrahedron formation through triangulation readily allows for both a fixed local position/orientation frame of reference as well as reconciliation to any required external frame of reference.
3) The tetrahedron is applicable to both individual physical targets and formations.

Both target and formation scale factors must be experimentally determined based on the sensible combination of far field and near field effects observed. It is anticipated that the combination of known formation geometry and the measurable differential response of rectenna elements will allow for very precise local position/orientation management.

IV. Technological Challenges

The first principles physics of both “near field” and “far field” energy effects are considered well understood. However, the use of radiant energy (by definition a far field effect, a.k.a. “Beaming”) to transfer (power, data, force, heat) on an optimized basis (particularly at far field-near field boundaries) either directly and/or by inducing near field effects at a distance is less understood at least from the stand point 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.

A.Radiant Energy Beam Components

For the purposes of this work we have defined the radiant energy beam components to include:

1) Electrical
2) Magnetic
3) Linear & Angular Momentum
4) Thermal
5) 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.).

In theory, the use of the component interactions can enable:

1) Individual knowledge of position and orientation
2) Shared knowledge loose coupling /interfaces between related objects
3) Near network control (size to sense/proportionality to enable desired control)
4) Fixed and/or rotating beam projections
5) Potential for net velocity along any specified vector

V. Mission Team

The following organizations, entities, and/or individuals have notified XISP-Inc of their interest in cooperation/collaboration with respect to this mission:

A. Commercial Entities

1) Xtraordinary Innovative Space Partnerships, Inc. - Gary Barnhard, et al.
2) Barnhard Associates, LLC - Gary Barnhard, et al.
3) Raytheon, Inc. – Hooman Kazemi, et al.
4) OrbitalATK – Bob Richards, et al.
5) Immortal Data Inc. – Dale Amon, et al.
6) Deep Space Industries, Inc - Peter Stibrany, et al.
7) Center for the Advancement of Science In Space (CASIS) – Jennifer Lopez, et al.
8) Nanoracks Inc. – Chad Brinkley, et al.
9) Made In Space, Inc. – Jason Dunn, et al.
10) EXOS Aerospace & Technologies, Inc. – John Quinn, et al.
11) Tethers Unlimited, Inc. – Rob Hoyt, et al.
12) Power Correction System, Inc – Brahm Segal, et.al

B. Universities:

1) University of New Mexico Configurable Space Microsystems Innovations and Applications Center (COSMIAC) - Christos Christodoulou, et al.
2) University of Maryland Space Systems Lab – David Akin, et.al
3) MIT Space Systems Lab – Alvar Saenz-Otero, et al.
4) University of North Dakota Space Systems Lab – Sima Noghanian, et al.
5) Saint Louis University Space Systems Lab – Michael Swartwout, et al.

C. Government Agencies:

1) NASA Headquarters Human Exploration & Operations Mission Directorate
    a. Advanced Exploration Systems Division, Jason Crusan, et al.
    b. Space Communications and Navigation Office, Jim Schier, et al.
2) Multiple NASA Centers will have some cooperating role – NASA ARC, et al.
3) U.S. Naval Research Lab – Paul Jaffe, et.al

D. Non-profit Organizations:

1) Space Development Foundation – David Dunlop, et al.
2) SPACECanada – George Dietrich, et al.
3) National Space Society

Multiple other commercial, educational, non-profit organizations, and ISS International Partners have expressed substantive interest in cooperation/collaboration with respect to this mission and are actively negotiating their potential role with XISP-Inc.

The XISP-Inc core team consists of:

- Gary Pearce Barnhard – Computer/Robotic/Space Systems Engineer, Space Solar Power technology/mission development, research work on the applications of knowledge based systems to the domain space systems engineering, research work on near real-time state models, research work on management operations control applications including process flow engineering problems, responsible for the ISS Robotic Systems Integration Standards (RSIS) development, responsible for the ISS external utility port standardization effort, responsible for the ISS system level requirements for advanced automation and robotics.
- Daniel Ray Faber – Spacecraft systems/subsystems systems engineering and development, transmitter and receiver development.
- John Mankins – Former NASA Headquarters Technology Development portfolio lead, Space Solar Power technology development and demonstration.
- Paul Werbos – former NSF program director for energy, intelligent systems, and modeling for electronic systems and devices. Lead director for the last actual NSF funding initiative in https://nsf.gov/pubs/2002/nsf02098/nsf02098.pdf Space Solar Power technology development and demonstration.
- Seth Potter – Space Systems Engineer, Space Solar Power technology development, demonstration, and deployment, Beam forming.
- Paul Jaffe – Space Solar Power technology development and demonstration.
- James McSpadden – Microwave systems engineer.

- - - Additional XISP-Inc Staff & Consultants - - -

- Joseph Rauscher – Cooperative and colaborative agreement development, Federal programs development
- Brad Blair – Space mining engineering, exo-geology, and economic analysis.
- Brahm Segal – RF/Power systems engineering, test, verification & validation.
- Tim Cash – RF/Microwave systems engineering, test, verification & validation.
- Eric Dahlstrom – Astro-physics, mission development and space systems engineering.
- Michael Doty – Satellite/spacecraft systems engineering and integration.
- Aaron Harper – Communications and data systems research, development, and deployment
- Dale Amon – Data acquisition and control instrumentation.
- Doug Weathers – Electronics prototyping and software development.
- Tim Pickens – Advanced propulsion systems research, development, and deployment
- Ed Belbruno – Orbital dynamics, ballistic escape and return trajectory analysis.
- David Cheuvront – Space systems engineering, mission development, and economics/operations analysis.

VI. 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) 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 negotiated.

Additional partners/participants are being sought in the commercial, academic, non-profit, government, and international sectors. XISP-Inc is actively soliciting potential customers for all Cislunar addressable markets

- ISS Co-orbiting/LEO
- LEO/MEO/HEO/GEO
- Libration Point/Trajectory Insertion/Navigation Waypoints
- Lunar Resonance Ground Tracking Orbit
- Lunar Surface
- Asteroidal Surface

It is anticipated that the combination of the revenue from the power and ancillary services provided to ISS co-orbiting/LEO customers and the value of the perceived and/or real cost, schedule, and technical risks retired by the TD^3 mission will realize a large enough return to secure the follow-on investment required to build out the Lunar Power& Light Company.

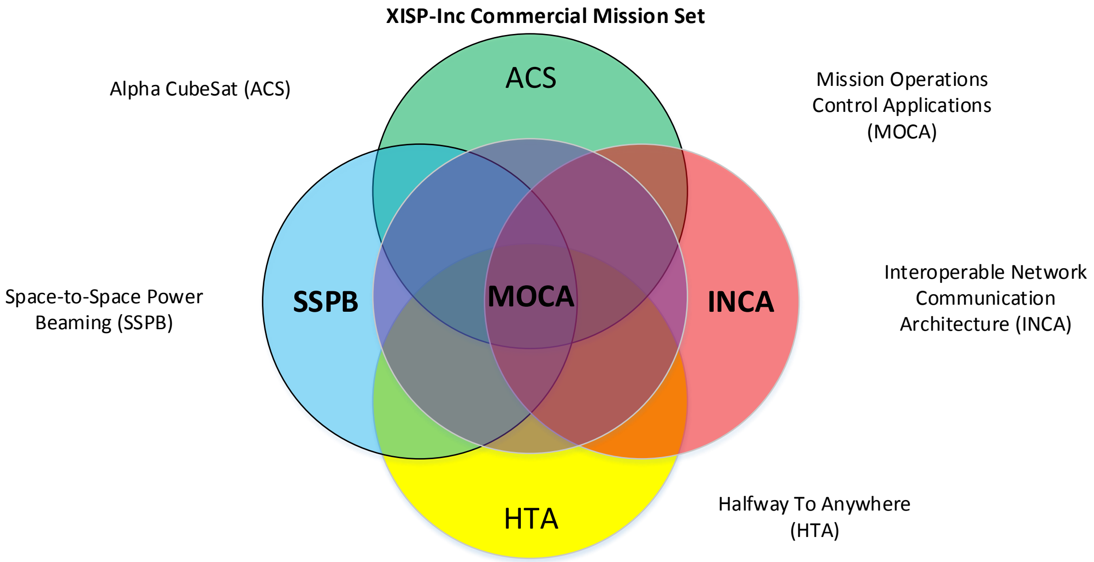
XISP-Inc is part of the ULA sponsored Cislunar Marketplace development effort involving over 150 entities.

There is an open market for degrading legacy systems in the near-term, an evolving market for new enhanced satellites in the mid-term (~2 to ~5 years) , and an essential element of “immortal” serviced platform systems that will be designed to accommodate multiple generations of payloads in the long-term (~5 to ~10 years). Any enhanced electrical power and ancillary services made available on an in situ and/or beamed basis to customers will be reflected directly as an increased ROI even after accounting for the recurring costs.

Any electrical power and allied utility services made available would prove to be mission enhancing if not mission enabling and has the potential for creating a reoccurring revenue stream.

The ability to augment available electrical power and/or transfer heat via a radiant energy beam can significant improve the performance of electrical as well as chemical propulsion systems (e.g., resistojets, etc.). Applications include orbital altitude and plane change, Cislunar and deep space trajectory insertion, as well as cycling transfers.

The combination of the XISP-Inc Alpha Cube Sat (ACS), SSPB, Interoperable Network Communication Architectures (INCA), Management Operations Control Applications (MOCA) and Halfway To Anywhere (HTA) missions serve as a resource for fostering the development of Cislunar utilities across the range of addressable markets as shown in Figure 2 – XISP-Inc Commercial Mission Set Venn Diagram. The combination of line-of-site high frequency microwave/laser transmission from lunar resonant ground tracking orbits which are long term stable with exceptionally close surface approach as well as surface mounted relay and proximity distribution systems can provide a range of power and allied utility service options for lunar facilities and related operations. ESA, JAXA, and NASA SCaN representatives have shown interest in understanding these options.



- ACS provides a technology development, demonstration, and deployment (TD^3) spacecraft bus for HTA, INCA, MOCA, and SSPB
  - ➔ Low cost configurable spacecraft for Earth facing, Cislunar infrastructure, and beyond Earth orbit applications.
- HTA provides TD^3 propulsion testbed, trajectory insertion bus, alternate minimum energy trajectories, and resonance orbits for ACS, INCA, MOCA and SSPB.
  - ➔ ISS as a transportation node for low cost, readily deployable Earth orbit, cislunar and beyond Earth orbit mission support.
- INCA provides TD^3 web accelerator, QoS routing/pervasively networked gateway, multi-core thermally managed computer resources, Xrosslink protocol, relay interface kits, for ACS, HTA, MOCA, and SSPB
  - ➔ Communications & Navigation Utilities and interface kits for Earth facing, on-orbit, and space facing mission support/ networks.
- MOCA provides TD^3 near realtime state models, mutable locus of control, and virtual operations center for ACS, HTA, INCA, and SSPB
  - ➔ Facilitate crewed, tele-operated/shared control, and autonomous in situ operations reducing crew time required for experiments and increasing ISS productivity.
- SSPB provides TD^3 radiant energy beaming testbed, and electrical utilities for ACS, HTA, INCA, and MOCA
  - ➔ Space-to-Space and Space-to-Alternate surface electrical utilities.

Figure 2. XISP-Inc Commercial Mission Set Venn Diagram

ACS illustrates the potential for cost effective long duration networks with short transmission distances and relatively low power requirements. Enhanced ACS like systems could illustrate the potential for laser power beaming with short transmission distances to transmit stay alive power to many points on the lunar surface.

The ISS testbed portion of the TD^3 mission results in terms of characterization, optimization, and operational rules as well as the resulting tested system data regarding distance, power and frequencies can be practically related to systems which could provide stay alive power on the lunar surface during the lunar night. It is anticipated that by projecting how much power and how often it could be provided during a 14 day lunar night we could foster the creation of market demand, for example in North and or South polar target areas.

Potential lunar surface customers include:

- Resource Prospector successor
- International Lunar Network locations
- Mobile surface rovers for long duration travel: Schroedinger Crater missions proposed by Kring et.al.
- ESA proposed Moon Village

XISP-Inc anticipated that there is a market for ancillary services (communications, data, navigation/time) and strategies for achieving an Interoperable Network Communication Architecture (INCA) as well as the Quality of Service (QoS) requirements (i.e., performance, availability, and security)

Frequency agnostic (e.g., Software Defined Radios, electro/optical converged electronics, and selectable apertures) pervasively networked communications and data systems with provisions for Delay and Disturbance Tolerant Networking (DTN) including store and forward capacity, and QoS based routing will likely be essential.

It is incumbent on XISP-Inc to establish the commercial merits of the Lunar Power & Light Company as a Public/Private Partnership opportunity worthy of NASA, International, and commercial partner participation.

The near term ISS TD^3 mission incorporating frequency agnostic (Ka band ➔ optical beaming) technology is a precursor for lunar addressable markets.

Beam pointing and targeting from an orbiting spacecraft to another target may be facilitated by low power RF, microwave, and/or laser guide beams.

A high value application of the SSPB ISS testbed is to prove out the utility of as well as reduce the cost, schedule, and technical risks associated with the asteroidal assay missions. The concept is that such missions will require one or more asteroid co-orbiting motherships which fractionate to deliver landed sensors packages that are provided power and allied utility services by radiant energy beaming.

Parallel work in sourcing power generation system alternatives including photovoltaic, solar concentrator, solar dynamic, and solar pumped lasers is essential to realizing the potential of a Cislunar electrical and ancillary services company (aka. Lunar Power & Light Company) and is now underway.

Opportunities for international cooperation leveraging the ISS Intergovernmental Agreements are being explored and developed. Use of ISS helps ensure that this is an international cooperative/collaborative TD^3 mission that moves forward in a transparent and well understood manner by the international community.

VII. Conclusion

Successful demonstration of space solar power beaming helps pave the way for its use in a range of space-to-space, space-to-lunar/infrastructure surface, and space-to-Earth applications by reducing the perceived cost, schedule, and technical risk of the technology.

Commercial space applications include mission enhancing and/or mission enabling expansion of operational mission time/capabilities, enhanced spacecraft/infrastructure design flexibility as well as out-bound orbital trajectory insertion propulsion.

Orchestraing the TD^3 mission to ensure that it is driven by what is required to meet commercial customer requirements necessitates a frequency agnostic approach to system engineering. Accordingly, technology development “push” is insufficient, mission requirements “pull” is essential to ensuring that actually meeting customer requirements is not lost in the process.

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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