Space-to-Space Power Beaming - A Commercial Mission to Unbundle Space Power Systems to Foster Space Applications

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One of many paths forward for hastening the development of viable applications of space solar power technology is through focused incremental technology development efforts. This work is intended to help mitigate the cost, schedule, and technical risk associated with the short, mid, and long term application of space solar power technology for space-to-space radiant energy beaming. This commercial mission will provide both a testbed environment for the technology and a capability of demonstrable value to some number of customers co-orbiting with the International Space Station (ISS).

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

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 efforts. These efforts can serve to mitigate 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 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 and a demonstrable value to some number of customers co-orbiting with the International Space Station (ISS). This paper provides an update on the mission development work to achieve the overarching mission objective -- unbundling space power systems (i.e., the separation of power generation, transmission, management, and loads)[7-24].

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. This effort bridges technology development, technology demonstration, and technology deployment. Furthermore, if 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.

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II. Mission Definition

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. Mission Hypothesis

XISP-Inc has hypothesized that 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:
    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.

B. Mission Impact

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
        i. communications
        ii. remote sensing
        iii. navigation
        iv. power

C. 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.

D. 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}

Theoretical Maximum Possible DC to DC Efficiency – 76%, circa 1992{use of one cycle modulation could increase this to between 85-95%, not pulse width modulation (pwn)}
Experimental DC to DC Efficiency – 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, the following equation can be used[1] .

$$p_d = (A_t)(P_t) / (\lambda)^2(D)^2 \quad (1)$$

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 test cases that have been calculated so far include:
Case 1: Ka Band Low 26.5 GHz,
λ=1.13 cm, $A_t = 1642$ cm^2 and 10000 cm^2, $P_t = 3000$ W and 6000 W, $D = 200$ m
Case 2: Ka Band Target 36 GHz,
λ=0.833 cm, $A_t = 1642$ cm^2 and 10000 cm^2, $P_t = 3000$ W and 6000 W, $D = 200$ m
Case 3: W Band Target 95 GHz,
λ=0.316 cm, $A_t = 1642$ cm^2 and 10000 cm^2, $P_t = 3000$ W and 6000 W, $D = 200$ m

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.
Area of proposed ISS W Band Transmitter Plate ~10000 cm^2
JEM Exposed Facility Utility Port Power ranges from 3000 W to 6000 W maximum, subject to availability.
ISS spherical zone of exclusion is 200 m radius from the center of mass.

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.

The received power can then be calculated from the following equation[1]:

$$P_r = (p_d)(A_r) \quad (2)$$

P_r is the power received [W]
p_d is the power density at the center of the receiving location [W/cm^2]
A_r is the total area of the receiving aperture [cm^2]

It is important to note that equations (1) and (2) are considered far-field equations and provide a good idea of the power received by rectenna aperture if the collection efficiency is low. However, it is possible using more developed equations to calculate the power collection efficiency between the transmitter and rectenna apertures. Results using the more developed equations differ from the far-field equations because they integrate power over the receiving aperture area. If a transmitters amplitude has taper the collection efficiency equations must be used. Further iterations of this work involve the use of more developed equations that take into consideration these issues and other near-field, boundary, and far-field considerations.[25]

The test cases that have been calculated so far include:

Case 1: Ka Band Low 26.5 GHz

λ=1.13 cm, A_t = 1642 cm^2, P_t = 3000 W, D = 200 m

$p_d = (A_t)(P_t) / (\lambda)^2(D)^2 = 0.00964$ W/cm^2

A_r = 100 cm^2 to 10000 cm^2

$P_r = (p_d)(A_r)$ = see Table 1. Power Received with P_t = 3000 W and A_t = 1642 cm^2

Case 2: Ka Band Target 36 GHz,

λ=0.833 cm, A_t = 1642 cm^2, P_t = 3000 W, D = 200 m

$p_d = (A_t)(P_t) / (\lambda)^2(D)^2 = 0.01774$ W/cm^2

A_r = 100 cm^2 to 10000 cm^2

$P_r = (p_d)(A_r)$ = see Table 1. Power Received with P_t = 3000 W and A_t = 1642 cm^2

Case 3: W Band Target 95 GHz,

λ=0.316 cm, A_t = 1642 cm^2, P_t = 3000 W, D = 200 m

$p_d = (A_t)(P_t) / (\lambda)^2(D)^2 = 0.12331$ W/cm^2

A_r = 100 cm^2 to 10000 cm^2

$P_r = (p_d)(A_r)$ = see Table 1. Power Received with 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									CASE 2 - Space Station Ka Band Transmitter Anticipated Power Received for various rectenna areas - Ka Target 36 GHz									CASE 3 - Optimized W Band Transmitter Anticipated Power Received for various rectenna areas W Target 95 GHz								
Distance	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received		Distance	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received		Distance	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	**=**	**Pd**	*****	**Ar**					**Pr**	**=**	**Pd**	*****	**Ar**					**Pr**	**=**	**Pd**	*****	**Ar**			
200 m	Pr	=	0.009643	*	**100**	=	**0.96**	watts	200 m	Pr	=	0.017745	*	**100**	=	**1.77**	watts	200 m	Pr	=	0.123307	*	**100**	=	**12.33**	watts
200 m	Pr	=	0.009643	*	**200**	=	**1.93**	watts	200 m	Pr	=	0.017745	*	**200**	=	**3.55**	watts	200 m	Pr	=	0.123307	*	**200**	=	**24.66**	watts
200 m	Pr	=	0.009643	*	**300**	=	**2.89**	watts	200 m	Pr	=	0.017745	*	**300**	=	**5.32**	watts	200 m	Pr	=	0.123307	*	**300**	=	**36.99**	watts
200 m	Pr	=	0.009643	*	**400**	=	**3.86**	watts	200 m	Pr	=	0.017745	*	**400**	=	**7.10**	watts	200 m	Pr	=	0.123307	*	**400**	=	**49.32**	watts
200 m	Pr	=	0.009643	*	**500**	=	**4.82**	watts	200 m	Pr	=	0.017745	*	**500**	=	**8.87**	watts	200 m	Pr	=	0.123307	*	**500**	=	**61.65**	watts
200 m	Pr	=	0.009643	*	**600**	=	**5.79**	watts	200 m	Pr	=	0.017745	*	**600**	=	**10.65**	watts	200 m	Pr	=	0.123307	*	**600**	=	**73.98**	watts
200 m	Pr	=	0.009643	*	**700**	=	**6.75**	watts	200 m	Pr	=	0.017745	*	**700**	=	**12.42**	watts	200 m	Pr	=	0.123307	*	**700**	=	**86.32**	watts
200 m	Pr	=	0.009643	*	**800**	=	**7.71**	watts	200 m	Pr	=	0.017745	*	**800**	=	**14.20**	watts	200 m	Pr	=	0.123307	*	**800**	=	**98.65**	watts
200 m	Pr	=	0.009643	*	**900**	=	**8.68**	watts	200 m	Pr	=	0.017745	*	**900**	=	**15.97**	watts	200 m	Pr	=	0.123307	*	**900**	=	**110.98**	watts
200 m	Pr	=	0.009643	*	**1000**	=	**9.64**	watts	200 m	Pr	=	0.017745	*	**1000**	=	**17.74**	watts	200 m	Pr	=	0.123307	*	**1000**	=	**123.31**	watts
200 m	Pr	=	0.009643	*	**2000**	=	**19.29**	watts	200 m	Pr	=	0.017745	*	**2000**	=	**35.49**	watts	200 m	Pr	=	0.123307	*	**2000**	=	**246.61**	watts
200 m	Pr	=	0.009643	*	**3000**	=	**28.93**	watts	200 m	Pr	=	0.017745	*	**3000**	=	**53.23**	watts	200 m	Pr	=	0.123307	*	**3000**	=	**369.92**	watts
200 m	Pr	=	0.009643	*	**4000**	=	**38.57**	watts	200 m	Pr	=	0.017745	*	**4000**	=	**70.98**	watts	200 m	Pr	=	0.123307	*	**4000**	=	**493.23**	watts
200 m	Pr	=	0.009643	*	**5000**	=	**48.21**	watts	200 m	Pr	=	0.017745	*	**5000**	=	**88.72**	watts	200 m	Pr	=	0.123307	*	**5000**	=	**616.54**	watts
200 m	Pr	=	0.009643	*	**6000**	=	**57.86**	watts	200 m	Pr	=	0.017745	*	**6000**	=	**106.47**	watts	200 m	Pr	=	0.123307	*	**6000**	=	**739.84**	watts
200 m	Pr	=	0.009643	*	**7000**	=	**67.50**	watts	200 m	Pr	=	0.017745	*	**7000**	=	**124.21**	watts	200 m	Pr	=	0.123307	*	**7000**	=	**863.15**	watts
200 m	Pr	=	0.009643	*	**8000**	=	**77.14**	watts	200 m	Pr	=	0.017745	*	**8000**	=	**141.96**	watts	200 m	Pr	=	0.123307	*	**8000**	=	**986.46**	watts
200 m	Pr	=	0.009643	*	**9000**	=	**86.79**	watts	200 m	Pr	=	0.017745	*	**9000**	=	**159.70**	watts	200 m	Pr	=	0.123307	*	**9000**	=	**1109.77**	watts
200 m	Pr	=	0.009643	*	**10000**	=	**96.43**	watts	200 m	Pr	=	0.017745	*	**10000**	=	**177.45**	watts	200 m	Pr	=	0.123307	*	**10000**	=	**1233.07**	watts

Table 1. Power Received with P_t= 3000 W and A_t = 1642 cm^2

Case 1: Ka Band Low 26.5 GHz

λ=1.13 cm, A_t = 1642 cm^2, P_t = 6000 W, D = 200 m

$p_d = (A_t)(P_t) / (\lambda)^2(D)^2 = 0.01929$ W/cm^2

A_r = 100 cm^2 to 10000 cm^2

$P_r = (p_d)(A_r)$ = see Table 2. Power Received with P_t = 6000 W and A_t = 1642 cm^2

Case 2: Ka Band Target 36 GHz,

λ=0.833 cm, A_t = 1642 cm^2, P_t = 6000 W, D = 200 m

$p_d = (A_t)(P_t) / (\lambda)^2(D)^2 = 0.03549$ W/cm^2

A_r = 100 cm^2 to 10000 cm^2

$P_r = (p_d)(A_r)$ = see Table 2. Power Received with P_t = 6000 W and A_t = 1642 cm^2

Case 3: W Band Target 95 GHz,

λ=0.316 cm, A_t = 1642 cm^2, P_t = 6000 W, D = 200 m

$p_d = (A_t)(P_t) / (\lambda)^2(D)^2 = 0.24661$ W/cm^2

A_r = 100 cm^2 to 10000 cm^2

$P_r = (p_d)(A_r)$ = see Table 2. Power Received with 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	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	=	Pd	*	Ar			
200 m	Pr	=	0.019286	*	**100**	=	**1.93**	watts
200 m	Pr	=	0.019286	*	**200**	=	**3.86**	watts
200 m	Pr	=	0.019286	*	**300**	=	**5.79**	watts
200 m	Pr	=	0.019286	*	**400**	=	**7.71**	watts
200 m	Pr	=	0.019286	*	**500**	=	**9.64**	watts
200 m	Pr	=	0.019286	*	**600**	=	**11.57**	watts
200 m	Pr	=	0.019286	*	**700**	=	**13.50**	watts
200 m	Pr	=	0.019286	*	**800**	=	**15.43**	watts
200 m	Pr	=	0.019286	*	**900**	=	**17.36**	watts
200 m	Pr	=	0.019286	*	**1000**	=	**19.29**	watts
200 m	Pr	=	0.019286	*	**2000**	=	**38.57**	watts
200 m	Pr	=	0.019286	*	**3000**	=	**57.86**	watts
200 m	Pr	=	0.019286	*	**4000**	=	**77.14**	watts
200 m	Pr	=	0.019286	*	**5000**	=	**96.43**	watts
200 m	Pr	=	0.019286	*	**6000**	=	**115.71**	watts
200 m	Pr	=	0.019286	*	**7000**	=	**135.00**	watts
200 m	Pr	=	0.019286	*	**8000**	=	**154.29**	watts
200 m	Pr	=	0.019286	*	**9000**	=	**173.57**	watts
200 m	Pr	=	0.019286	*	**10000**	=	**192.86**	watts

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

Distance	Power Receive		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	=	Pd	*	Ar			
200 m	Pr	=	0.035490	*	**100**	=	**3.55**	watts
200 m	Pr	=	0.035490	*	**200**	=	**7.10**	watts
200 m	Pr	=	0.035490	*	**300**	=	**10.65**	watts
200 m	Pr	=	0.035490	*	**400**	=	**14.20**	watts
200 m	Pr	=	0.035490	*	**500**	=	**17.74**	watts
200 m	Pr	=	0.035490	*	**600**	=	**21.29**	watts
200 m	Pr	=	0.035490	*	**700**	=	**24.84**	watts
200 m	Pr	=	0.035490	*	**800**	=	**28.39**	watts
200 m	Pr	=	0.035490	*	**900**	=	**31.94**	watts
200 m	Pr	=	0.035490	*	**1000**	=	**35.49**	watts
200 m	Pr	=	0.035490	*	**2000**	=	**70.98**	watts
200 m	Pr	=	0.035490	*	**3000**	=	**106.47**	watts
200 m	Pr	=	0.035490	*	**4000**	=	**141.96**	watts
200 m	Pr	=	0.035490	*	**5000**	=	**177.45**	watts
200 m	Pr	=	0.035490	*	**6000**	=	**212.94**	watts
200 m	Pr	=	0.035490	*	**7000**	=	**248.43**	watts
200 m	Pr	=	0.035490	*	**8000**	=	**283.92**	watts
200 m	Pr	=	0.035490	*	**9000**	=	**319.41**	watts
200 m	Pr	=	0.035490	*	**10000**	=	**354.90**	watts

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

Distance	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	=	Pd	*	Ar			
200 m	Pr	=	0.246615	*	**100**	=	**24.66**	watts
200 m	Pr	=	0.246615	*	**200**	=	**49.32**	watts
200 m	Pr	=	0.246615	*	**300**	=	**73.98**	watts
200 m	Pr	=	0.246615	*	**400**	=	**98.65**	watts
200 m	Pr	=	0.246615	*	**500**	=	**123.31**	watts
200 m	Pr	=	0.246615	*	**600**	=	**147.97**	watts
200 m	Pr	=	0.246615	*	**700**	=	**172.63**	watts
200 m	Pr	=	0.246615	*	**800**	=	**197.29**	watts
200 m	Pr	=	0.246615	*	**900**	=	**221.95**	watts
200 m	Pr	=	0.246615	*	**1000**	=	**246.61**	watts
200 m	Pr	=	0.246615	*	**2000**	=	**493.23**	watts
200 m	Pr	=	0.246615	*	**3000**	=	**739.84**	watts
200 m	Pr	=	0.246615	*	**4000**	=	**986.46**	watts
200 m	Pr	=	0.246615	*	**5000**	=	**1233.07**	watts
200 m	Pr	=	0.246615	*	**6000**	=	**1479.69**	watts
200 m	Pr	=	0.246615	*	**7000**	=	**1726.30**	watts
200 m	Pr	=	0.246615	*	**8000**	=	**1972.92**	watts
200 m	Pr	=	0.246615	*	**9000**	=	**2219.53**	watts
200 m	Pr	=	0.246615	*	**10000**	=	**2466.15**	watts

Table 2. Power Received with P_t= 6000 W and A_t = 1642 cm^2

Case 1: Ka Band Low 26.5 GHz

λ=1.13 cm, A_t = 10000 cm^2, P_t = 3000 W, D = 200 m

$p_d = (A_t)(P_t) / (\lambda)^2(D)^2 = 0.05874$ W/cm^2

A_r = 100 cm^2 to 10000 cm^2

$P_r = (p_d)(A_r)$ = see Table 3. Power Received with P_t = 3000 W and A_t = 10000 cm^2

Case 2: Ka Band Target 36 GHz,

λ=0.833 cm, A_t = 10000 cm^2, P_t = 3000 W, D = 200 m

$p_d = (A_t)(P_t) / (\lambda)^2(D)^2 = 0.10809$ W/cm^2

A_r = 100 cm^2 to 10000 cm^2

$P_r = (p_d)(A_r)$ = see Table 3. Power Received with P_t = 3000 W and A_t = 10000 cm^2

Case 3: W Band Target 95 GHz,

λ=0.316 cm, A_t = 10000 cm^2, P_t = 3000 W, D = 200 m

$p_d = (A_t)(P_t) / (\lambda)^2(D)^2 = 0.75108$ W/cm^2

A_r = 100 cm^2 to 10000 cm^2

$P_r = (p_d)(A_r)$ = see Table 3. Power Received with 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	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	=	Pd	*	Ar			
200 m	Pr	=	0.058736	*	**100**	=	**5.87**	watts
200 m	Pr	=	0.058736	*	**200**	=	**11.75**	watts
200 m	Pr	=	0.058736	*	**300**	=	**17.62**	watts
200 m	Pr	=	0.058736	*	**400**	=	**23.49**	watts
200 m	Pr	=	0.058736	*	**500**	=	**29.37**	watts
200 m	Pr	=	0.058736	*	**600**	=	**35.24**	watts
200 m	Pr	=	0.058736	*	**700**	=	**41.12**	watts
200 m	Pr	=	0.058736	*	**800**	=	**46.99**	watts
200 m	Pr	=	0.058736	*	**900**	=	**52.86**	watts
200 m	Pr	=	0.058736	*	**1000**	=	**58.74**	watts
200 m	Pr	=	0.058736	*	**2000**	=	**117.47**	watts
200 m	Pr	=	0.058736	*	**3000**	=	**176.21**	watts
200 m	Pr	=	0.058736	*	**4000**	=	**234.94**	watts
200 m	Pr	=	0.058736	*	**5000**	=	**293.68**	watts
200 m	Pr	=	0.058736	*	**6000**	=	**352.42**	watts
200 m	Pr	=	0.058736	*	**7000**	=	**411.15**	watts
200 m	Pr	=	0.058736	*	**8000**	=	**469.89**	watts
200 m	Pr	=	0.058736	*	**9000**	=	**528.62**	watts
200 m	Pr	=	0.058736	*	**10000**	=	**587.36**	watts

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

Distance	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	=	Pd	*	Ar			
200 m	Pr	=	0.108086	*	**100**	=	**10.81**	watts
200 m	Pr	=	0.108086	*	**200**	=	**21.62**	watts
200 m	Pr	=	0.108086	*	**300**	=	**32.43**	watts
200 m	Pr	=	0.108086	*	**400**	=	**43.23**	watts
200 m	Pr	=	0.108086	*	**500**	=	**54.04**	watts
200 m	Pr	=	0.108086	*	**600**	=	**64.85**	watts
200 m	Pr	=	0.108086	*	**700**	=	**75.66**	watts
200 m	Pr	=	0.108086	*	**800**	=	**86.47**	watts
200 m	Pr	=	0.108086	*	**900**	=	**97.28**	watts
200 m	Pr	=	0.108086	*	**1000**	=	**108.09**	watts
200 m	Pr	=	0.108086	*	**2000**	=	**216.17**	watts
200 m	Pr	=	0.108086	*	**3000**	=	**324.26**	watts
200 m	Pr	=	0.108086	*	**4000**	=	**432.35**	watts
200 m	Pr	=	0.108086	*	**5000**	=	**540.43**	watts
200 m	Pr	=	0.108086	*	**6000**	=	**648.52**	watts
200 m	Pr	=	0.108086	*	**7000**	=	**756.61**	watts
200 m	Pr	=	0.108086	*	**8000**	=	**864.69**	watts
200 m	Pr	=	0.108086	*	**9000**	=	**972.78**	watts
200 m	Pr	=	0.108086	*	**10000**	=	**1080.86**	watts

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

Distance	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	=	Pd	*	Ar			
200 m	Pr	=	0.751082	*	**100**	=	**75.11**	watts
200 m	Pr	=	0.751082	*	**200**	=	**150.22**	watts
200 m	Pr	=	0.751082	*	**300**	=	**225.32**	watts
200 m	Pr	=	0.751082	*	**400**	=	**300.43**	watts
200 m	Pr	=	0.751082	*	**500**	=	**375.54**	watts
200 m	Pr	=	0.751082	*	**600**	=	**450.65**	watts
200 m	Pr	=	0.751082	*	**700**	=	**525.76**	watts
200 m	Pr	=	0.751082	*	**800**	=	**600.87**	watts
200 m	Pr	=	0.751082	*	**900**	=	**675.97**	watts
200 m	Pr	=	0.751082	*	**1000**	=	**751.08**	watts
200 m	Pr	=	0.751082	*	**2000**	=	**1502.16**	watts
200 m	Pr	=	0.751082	*	**3000**	=	**2253.24**	watts
~~200 m~~	~~Pr~~	~~=~~	~~0.751082~~	~~*~~	~~**4000**~~	~~=~~	~~**3004.33**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~0.751082~~	~~*~~	~~**5000**~~	~~=~~	~~**3755.41**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~0.751082~~	~~*~~	~~**6000**~~	~~=~~	~~**4506.49**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~0.751082~~	~~*~~	~~**7000**~~	~~=~~	~~**5257.57**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~0.751082~~	~~*~~	~~**8000**~~	~~=~~	~~**6008.65**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~0.751082~~	~~*~~	~~**9000**~~	~~=~~	~~**6759.73**~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~0.751082~~	~~*~~	~~**10000**~~	~~=~~	~~**7510.82**~~	~~watts~~

Table 3. Power Received with P_t= 3000 W and A_t = 10000 cm^2

Case 1: Ka Band Low 26.5 GHz

λ=1.13 cm, A_t = 10000 cm^2, P_t = 6000 W, D = 200 m

$p_d = (A_t)(P_t) / (\lambda)^2(D)^2 = 0.11747$ W/cm^2

A_r = 100 cm^2 to 10000 cm^2

$P_r = (p_d)(A_r)$ = see Table 4. Power Received with P_t = 6000 W and A_t = 10000 cm^2

Case 2: Ka Band Target 36 GHz,

λ=0.833 cm, A_t = 10000 cm^2, P_t = 6000 W, D = 200 m

$p_d = (A_t)(P_t) / (\lambda)^2(D)^2 = 0.21617$ W/cm^2

A_r = 100 cm^2 to 10000 cm^2

$P_r = (p_d)(A_r)$ = see Table 4. Power Received with P_t = 6000 W and A_t = 10000 cm^2

Case 3: W Band Target 95 GHz,

λ=0.316 cm, A_t = 10000 cm^2, P_t = 6000 W, D = 200 m

$p_d = (A_t)(P_t) / (\lambda)^2(D)^2 = 1.50216$ W/cm^2

A_r = 100 cm^2 to 10000 cm^2

$P_r = (p_d)(A_r)$ = see Table 4. Power Received with P_t = 6000 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	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	=	Pd	*	Ar			
200 m	Pr	=	0.117472	*	100	=	11.75	watts
200 m	Pr	=	0.117472	*	200	=	23.49	watts
200 m	Pr	=	0.117472	*	300	=	35.24	watts
200 m	Pr	=	0.117472	*	400	=	46.99	watts
200 m	Pr	=	0.117472	*	500	=	58.74	watts
200 m	Pr	=	0.117472	*	600	=	70.48	watts
200 m	Pr	=	0.117472	*	700	=	82.23	watts
200 m	Pr	=	0.117472	*	800	=	93.98	watts
200 m	Pr	=	0.117472	*	900	=	105.72	watts
200 m	Pr	=	0.117472	*	1000	=	117.47	watts
200 m	Pr	=	0.117472	*	2000	=	234.94	watts
200 m	Pr	=	0.117472	*	3000	=	352.42	watts
200 m	Pr	=	0.117472	*	4000	=	469.89	watts
200 m	Pr	=	0.117472	*	5000	=	587.36	watts
200 m	Pr	=	0.117472	*	6000	=	704.83	watts
200 m	Pr	=	0.117472	*	7000	=	822.30	watts
200 m	Pr	=	0.117472	*	8000	=	939.78	watts
200 m	Pr	=	0.117472	*	9000	=	######	watts
200 m	Pr	=	0.117472	*	10000	=	######	watts

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

Distance	Power Receive		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	=	Pd	*	Ar			
200 m	Pr	=	0.2161729	*	100	=	21.62	watts
200 m	Pr	=	0.2161729	*	200	=	43.23	watts
200 m	Pr	=	0.2161729	*	300	=	64.85	watts
200 m	Pr	=	0.2161729	*	400	=	86.47	watts
200 m	Pr	=	0.2161729	*	500	=	108.09	watts
200 m	Pr	=	0.2161729	*	600	=	129.70	watts
200 m	Pr	=	0.2161729	*	700	=	151.32	watts
200 m	Pr	=	0.2161729	*	800	=	172.94	watts
200 m	Pr	=	0.2161729	*	900	=	194.56	watts
200 m	Pr	=	0.2161729	*	1000	=	216.17	watts
200 m	Pr	=	0.2161729	*	2000	=	432.35	watts
200 m	Pr	=	0.2161729	*	3000	=	648.52	watts
200 m	Pr	=	0.2161729	*	4000	=	864.69	watts
200 m	Pr	=	0.2161729	*	5000	=	1080.86	watts
200 m	Pr	=	0.2161729	*	6000	=	1297.04	watts
200 m	Pr	=	0.2161729	*	7000	=	1513.21	watts
200 m	Pr	=	0.2161729	*	8000	=	1729.38	watts
200 m	Pr	=	0.2161729	*	9000	=	1945.56	watts
200 m	Pr	=	0.2161729	*	10000	=	2161.73	watts

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

Distance	Power Received		Power Density (watts/cm**2)		Rectenna Area (cm**2)		Power Received	
	Pr	=	Pd	*	Ar			
200 m	Pr	=	1.502163	*	100	=	150.22	watts
200 m	Pr	=	1.502163	*	200	=	300.43	watts
200 m	Pr	=	1.502163	*	300	=	450.65	watts
200 m	Pr	=	1.502163	*	400	=	600.87	watts
200 m	Pr	=	1.502163	*	500	=	751.08	watts
200 m	Pr	=	1.502163	*	600	=	901.30	watts
200 m	Pr	=	1.502163	*	700	=	1051.51	watts
200 m	Pr	=	1.502163	*	800	=	1201.73	watts
200 m	Pr	=	1.502163	*	900	=	1351.95	watts
200 m	Pr	=	1.502163	*	1000	=	1502.16	watts
200 m	Pr	=	1.502163	*	2000	=	3004.33	watts
200 m	Pr	=	1.502163	*	3000	=	4506.49	watts
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~4000~~	~~=~~	~~6008.65~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~5000~~	~~=~~	~~7510.82~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~6000~~	~~=~~	~~9012.98~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~7000~~	~~=~~	~~10515.14~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~8000~~	~~=~~	~~12017.30~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~9000~~	~~=~~	~~13519.47~~	~~watts~~
~~200 m~~	~~Pr~~	~~=~~	~~1.502163~~	~~*~~	~~10000~~	~~=~~	~~15021.63~~	~~watts~~

Table 4. Power Received with P_t= 6000 W and A_t = 10000 cm^2

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 calculations break down and the use of more developed equations is required.

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 the I_{sc} = Solar Constant at 1 AU = 0.1367 W/cm^2 is approximately an order of magnitude less than p_d for Case 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.

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

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

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) Deep Space Industries, Inc - Daniel Faber, et.al.
3) Center for the Advancement of Science In Space (CASIS) – David Zuniga, et.al.
4) Nanoracks Inc. – Chad Brinkley, et.al.
5) EXOS Aerospace – John Quinn, et.al.
6) 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
2) National Space Society
3) Institute for Domestic Energy and Alliance

E. Consultants/Advisors:
1) Paul Werbos
2) Seth Potter
3) Joseph Rauscher

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

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, and government sectors.

Opportunities for international cooperation leveraging the ISS Intergovernmental Agreement are being explored and developed. Use of ISS helps ensure that this is an international cooperative/collaborative research effort.

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.

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