Xtraordinary Innovative Space Partnerships, Inc (XISP-Inc) Proposal

ISS Space-to-Space Power Beaming (SSPB)

Submitted to

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for award under

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Table of Contents

2. Scientific/Technical and Management Section

Summary of Proposal

Introduction

The **ISS Space-to-Space Power Beaming** demonstration complements the 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 of radiant energy beaming technology to the point where it can be deployed in support of one or more missions (4 to 8/9).

Innovation

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 system test of in-space beamed power, advancing this technology to TRL 8/9. The primary innovation is the physical separation of electricity generation from point of use. This innovation 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 Table 1 - Unique Benefits of Space-to-Space Power Beaming Relative to the Current State-of-Art.

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

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 • 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

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

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.

Results

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.

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: 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 b. opening new opportunities for shared orbital platforms, including but not limited to: communications, remote sensing, navigation, 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 can serve 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.)

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 TD3 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 extending the work to higher frequencies up through optical where warranted.
3) The use of simplified delivery to ISS of enhanced equipment and/or flight test articles as soft pack cargo from Earth.
4) The use of the Japanese Kibo laboratory airlock (and/or the planned commercial airlock) to transition flight systems to the EVA environment.
5) The use of the Mobile Servicing Center to provide enhanced deployment and retrieval capabilities.
6) 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., Dragon, Cygnus, HTX, 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.

Experience

- 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 and demonstration, Beam Forming.
- Paul Jaffe – Space Solar Power technology development and demonstration.
- James McSpadden – Microwave systems engineer.

Risk

XISP-Inc will employ a risk log table approach documenting all identified areas of technical, cost, and schedule risk, including the Risk #, Risk Title, Category, Raised By Name, Description, Causes, Date Raised, Date Last Updated, Likelihood, Consequences, Risk Rating, Counter Measures, Actions, Comments, Status, as well as calculated Likelihood, Consequences, and Risk Rating Values. While multiple aspects of this mission proposal involve unique applications most if not all of the individual operations have significant precedents. Launching non-toxic cubesat scale spacecraft as commercial pressurized cargo for release from the ISS to nadir biased destinations is now considered routine operations. This includes the use of CYCLOPS, and the JEM RMS. The use of the MSC for captive testing as well as release from the ISS to zenith biased destinations is a planned evolution based on a history of successful EVR operations. There are multiple Radio Frequency (RF) emitters on the ISS operating in different frequency bands. The addition of optimized Ka band and/or W band transmitters will be subject to the same analysis constraints as all other RF emitters to ensure compatibility/non-interference with the ISS operational environment. The release of a cubesat scale spacecraft which maintains a co-orbiting location (Ram, Starboard, Zenith bias) just outside the ISS Keep Out Sphere (KOS -- 200 m from the center of mass) using an active Guidance, Navigation and Control (GN&C) / Attitude Control System (ACS) and a non-toxic low thrust propulsion system (H_2O propellant) is novel but can be tested in parts and analytically verified as non-hazardous to the ISS. The proposed location due to a combination of orbital mechanics and standard ISS operating procedures will mitigate the risk of inadvertent entry into the KOS.

Cost

The total estimated cost cash and in-kind for the proposed twenty-four (24) month mission is approximately $6,916,106 split 50/50 between government direct & indirect investment and commercial cash and in-kind investment. This budget was developed by a combination of two methods: (1) On a “Top Down” basis driven by prevailing funding authority constraints including assumed maximum duration for the first increment, Federal Acquisition Regulations, solicitation guidance, reasonable labor category/rate/hour allocations, and tractable business operations considerations. (2) On a “Bottom Up” basis by actual labor category/rate/hour allocation estimates by work package and contracting items as outlined in the Work Breakdown

Structure supported by a combination of in-house estimates, consultant/subcontractor/supplier quotes, solicitation guidance, and tractable business operations considerations. The Pro Forma Budget provided is a synthesis of these two approaches which is intended to provide for the successful cost-effective, timely performance of the proposed work. If necessary, the mission scope can be scaled to match available funds and/or rebalanced to emphasize the highest priority outcomes. The detailed budget also provided adds additional information to support the evaluation process.

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 Technology Development, Demonstration, and Deployment (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:

- 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.
- 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.
- 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.
- 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.

<u>Experiment Objectives</u>

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.

<u>Innovation</u>

The innovation with respect to this work includes being the first Space-to-Space TD3 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.

<u>Results</u>

This mission will result in a SSPB 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.

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: 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, 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: a. enabling multiple plug-in and plug-out interfaces, and b. opening new opportunities for shared orbital platforms, including but not limited to: communications, remote sensing, navigation, and power

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.

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.

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?"

<u>SSPB & Commercial Requirements</u>

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 test cells
3) Propulsion (delta-V augmentation)
   a. Outbound & 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 ad hoc Communications & Navigation mesh networks
5) Operational Cadence/Cycle Evolution
   a. International Lunar Decade Support
6) Potential backup systems for the above uses.

Required Equipment

This mission requires the following equipment to be built/purchased:

1) ISS Transmitter (Vendor(s))
   - Ka Band Optimized transmitter (if existing ISS systems are not available or are unsuitable)
   - W Band Optimized transmitter (Raytheon, Tethers Unlimited, or others)
   - Optimized other band transmitter (scar only at this point)
2) Satellite Bus (Vendor(s))
   - 6U Bus Structure (Astrodigital, Tyvak, or others)
   - Electrical Power System w/reflectarray solar array Tx/Rx antenna (1< sq m) - (Bus vendor)
   - Data Management System – Blue Canyon
   - Guidance Navigation & Control (GN&C) / Attitude Control System (ACS) – Blue Canyon
   - Thermal Control System (passive) – (systems engineering)
   - Communications System (Ka Band) – (Tethers Unlimited, Blue Canyon, or others)
   - Propulsion System (H_2O propellant) – (DSI, Tethers Unlimited, or Phase 4)
3) Payload – Rectenna (Vendor(s))
   - Ka Band Rectenna for satellite bus reflectarray solar panel and Tx/Rx antenna - (Raytheon)
   - W Band Rectenna for satellite bus reflectarray solar panel and Tx/Rx antenna - (Raytheon)
   - Data Capture & Analysis System (Immortal Data)
   - Printed Protoflight Rectenna - (Made In Space and/or others)
   - Printed On-orbit Rectenna - (Made In Space)

Required Facilities

This mission requires the following facilities:

1) Mission management work environment (~48 sq m) – (XISP-Inc)
2) Collaborative internet based systems engineering work environment (XISP-Inc)
3) Integration lab (~28 sq m) - (XISP-Inc or vendor facility)
4) Bus Ground Test (Integration lab or vendor facility)
5) Payload Ground Test (Integration lab or vendor facility)
6) Temperature/Vacuum Test (Vendor facility ➔ Naval Research Lab)
7) EMI/EMC Ground Test (Vendor facility ➔ Naval Research Lab)
8) Bus/Payload Integration - (Vendor facility)
9) GN&C/ACS Validation – Simulation and mixed mode testing (Vendor facility)
10) On Orbit Test – (ISS)

Required Services

This mission requires the following services:

1) Mission management team (XISP-Inc)
2) Systems engineering team (XISP-Inc, Bus vendor, Consortium)
3) Research team (XISP-Inc, Payload vendor, Consortium)
4) Allied business services team (XISP-Inc, et.al.)

Work Plan

Figure 1 – Satellite Bus Astrodigital conceptual exterior w/o reflectarray panels

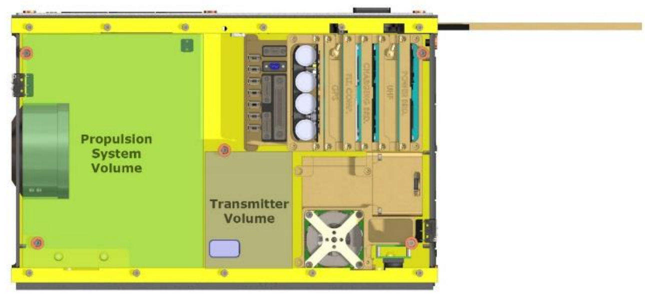
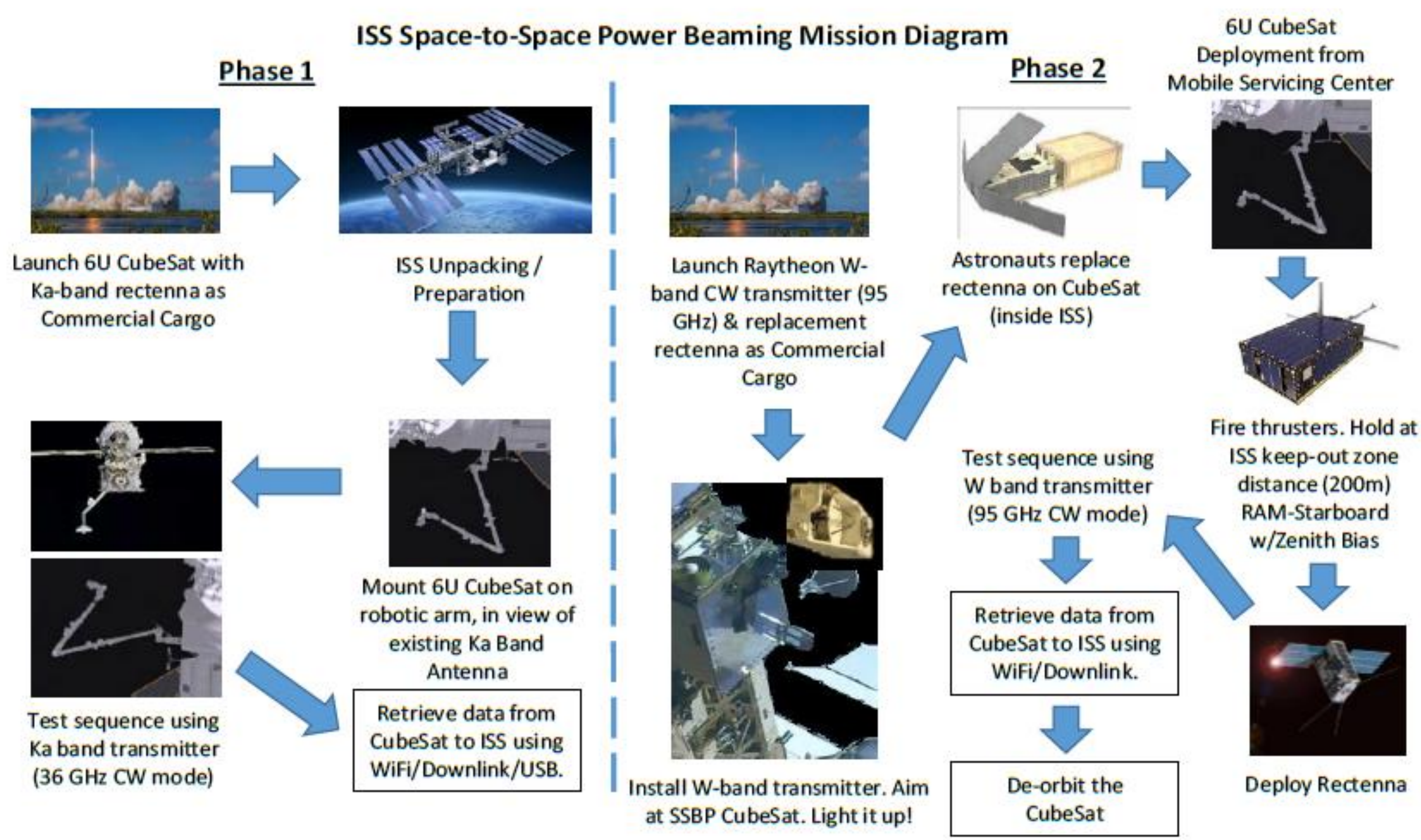


Figure 2 – Satellite Bus Astrodigital conceptual volumetric layout

This concept of operations is summarized in Figure 3 – ISS Space-to-Space Power Beaming Mission Diagram.

{The master schedule is shown on Figure 4 – ISS Space-to-Space Power Beaming (SSPB) Master Schedule January 13, 2017 Revision B}

{The Work Breakdown Schedule is shown in Figure 5 – XISP-Inc ISS Space-to-Space Power Beaming (SSPB) Work Breakdown Structure Schedule January 20, 2017 Revision A}


ISS Space-to-Space Power Beaming Mission Diagram
Phase 1
Launch 6U CubeSat with Ka-band rectenna as Commercial Cargo
ISS Unpacking / Preparation
Mount 6U CubeSat on robotic arm, in view of existing Ka Band Antenna
Test sequence using Ka band transmitter (36 GHz CW mode)
Retrieve data from CubeSat to ISS using WiFi/Downlink/USB.
Phase 2
Launch Raytheon W-band CW transmitter (95 GHz) & replacement rectenna as Commercial Cargo
Install W-band transmitter. Aim at SSBP CubeSat. Light it up!
Astronauts replace rectenna on CubeSat (inside ISS)
6U CubeSat Deployment from Mobile Servicing Center
Fire thrusters. Hold at ISS keep-out zone distance (200m) RAM-Starboard w/Zenith Bias
Deploy Rectenna
Test sequence using W band transmitter (95 GHz CW mode)
Retrieve data from CubeSat to ISS using WiFi/Downlink.
De-orbit the CubeSat

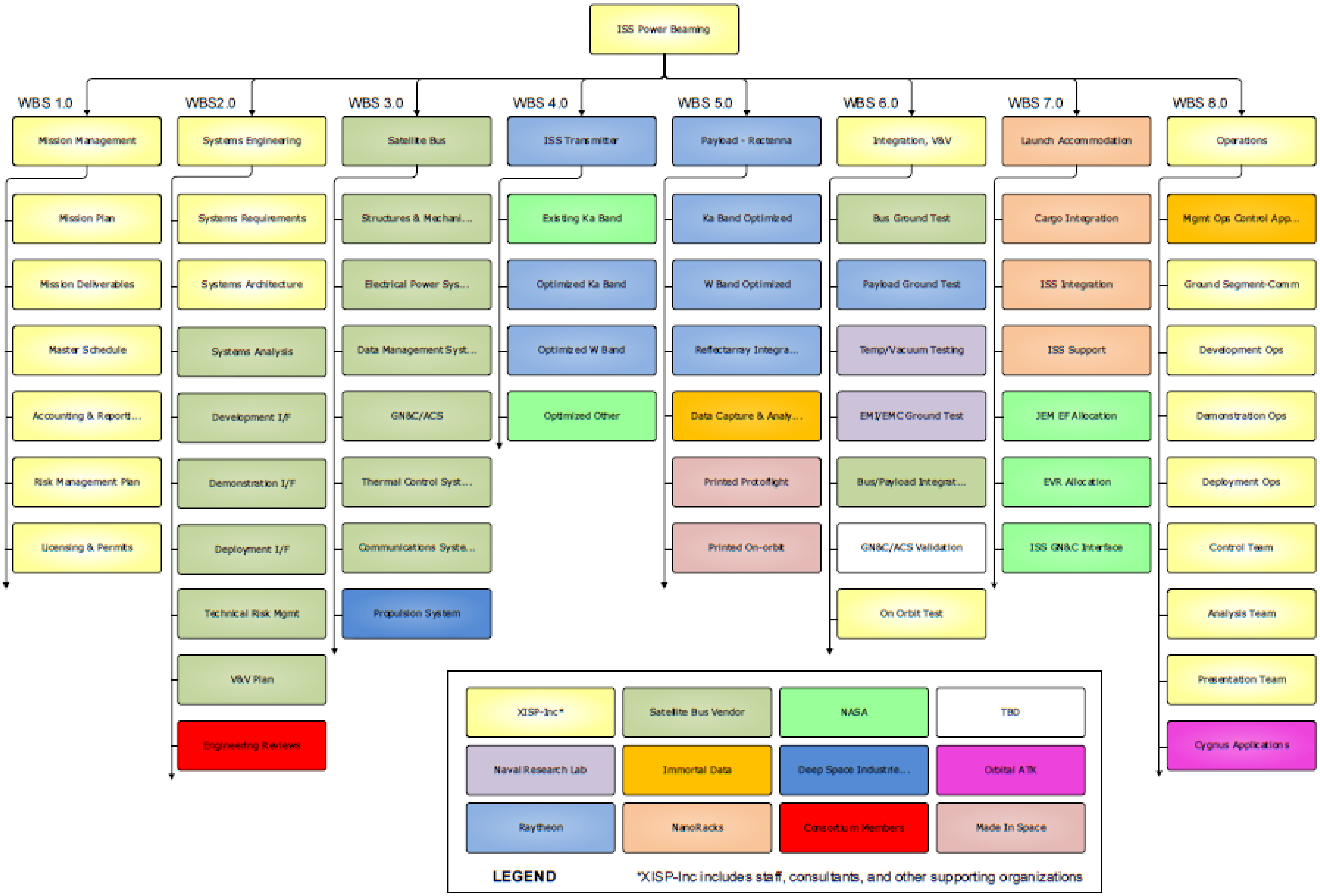
ISS Space-to-Space Power Beaming (SSPB) Master Schedule January 13, 2017 Revision B

WBS #	WBS Element Name	Kick-Off	MDR-I	PDR-I	CDR-I	FRR-I	Launch-I	FOP-I	MDR-II	PDR-II	CDR-II	FRR-II	Launch-II	FOP-II	FPR
1	**Mission Management**														
1.1	**Mission Plan**														
1.1.1	Statement of Work	1	2	--	--	--	--	--	3	--	--	--	--	--	X
1.1.2	Work Breakdown Structure	1	2	--	--	--	--	--	3	--	--	--	--	--	X
1.1.3	Milestone Schedule	1	2	--	--	--	--	--	3	--	--	--	--	--	X
1.1.4	Finalized Contract/Budget	X	--	--	--	--	--	--	--	--	--	--	--	--	--
1.2	**Mission Deliverables**														
1.2.1	Mission Status Reports (Monthly)	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1.3	Master Schedule	1	2	3	4	5	6	7	8	9	10	11	12	13	X
1.4	Accounting & Reporting	1	2	3	4	5	6	7	8	9	10	11	12	13	X
1.5	Risk Management Plan	1	2	3	4	X	--	--	6	7	8	9	--	--	X
1.5.1	Technical Risk Management	--	1	2	3	X	--	--	4	5	6	X	--	--	X
1.5.2	Schedule Risk Management	--	1	2	3	X	--	--	4	5	6	X	--	--	X
1.5.3	Cost Risk Management	--	1	2	3	X	--	--	4	5	6	X	--	--	X
1.6	Licensing & Permits	1	2	3	4	X	--	--	6	7	8	9	--	--	X
1.6.1	Frequency Allocation Plan	1	2	3	4	X	--	--	5	6	7	X	--	--	X
2	**Systems Engineering**														
2.1	Systems Requirements	1	2	3	4	5	--	--	6	7	8	9	--	--	X
2.1.1	Launch Requirements	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.1.2	On-orbit Requirements	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.1.3	Investigation Objectives & Research Plan	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.1.4	Systems Requirements Flow Down	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.2	Systems Architecture														
2.2.1	Concept of Operations Plan	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.2.1.1	Commercial Cargo Launch	--	--	--	X	--	--	--	--	--	X	--	--	--	--
2.2.1.2	ISS Deployment & Operations	--	--	--	X	--	--	--	--	--	X	--	--	--	--
2.2.2	Orbital Debris Assessment Report	--	--	--	X	--	--	--	--	--	X	--	--	--	--
2.2.3	Certification of Flight Readiness (CoFR)	--	--	--	--	X	--	--	--	--	--	X	--	--	--
2.2.4	Technology Development Plan	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.2.4.1	Knowledge Base	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.2.4.1.1	Intellectual Commons	--	--	X	--	--	--	--	--	X	--	--	--	--	--
2.2.4.1.2	Patents & Patents Pending	--	--	X	--	--	--	--	--	X	--	--	--	--	--
2.2.4.1.3	Trade Secrets	--	--	X	--	--	--	--	--	X	--	--	--	--	--
2.2.4.1.4	Known Unknowns	--	--	X	--	--	--	--	--	X	--	--	--	--	--
2.2.4.2	End-to-End State Models	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.2.4.2.1	Unbundled Electrical Power System	--	--	--	--	X	--	--	--	--	--	X	--	--	--
2.2.4.2.2	Spacecraft Systems-of-Systems	--	--	--	--	X	--	--	--	--	--	X	--	--	--
2.2.4.3	Beam Sources Plan	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.2.4.3.1	Existing Ground Infrastructure	--	--	--	--	--	--	--	--	--	--	--	--	--	--
2.2.4.3.2	Existing ISS Infrastructure	--	--	--	--	--	--	--	--	--	--	--	--	--	--
2.2.4.3.3	Software Defined Radios/Transceivers	--	--	--	--	--	--	--	--	--	--	--	--	--	--
2.2.4.3.3.1	26.5 GHz (Ka Band Low) - Reference Only	--	--	--	--	X	--	--	--	--	--	--	--	--	--
2.2.4.3.3.2	36 GHz (Ka Band High)	--	--	--	--	X	--	--	--	--	--	X	--	--	--
2.2.4.3.3.3	95 GHz (W Band)	--	--	--	--	--	--	--	--	--	--	X	--	--	--
2.2.4.3.3.4	Higher Fequencies through Optical - Scar for future	--	--	--	--	--	--	--	--	--	--	--	--	--	--
2.2.4.3.3.5	Radiant Energy Beam Forming	--	--	X	--	--	--	--	--	X	--	--	--	--	--
2.2.4.4	Rectenna Plan	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.2.4.4.1	2D - Definition, Geometry, Tuning	--	--	X	--	--	--	--	--	X	--	--	--	--	--
2.2.4.4.2	3D - Definition, Geometry, Tuning	--	--	X	--	--	--	--	--	X	--	--	--	--	--
2.2.4.4.3	Reflectarray	--	--	X	--	--	--	--	--	X	--	--	--	--	--
2.2.4.4.3.1	Integrated Rectenna	--	--	X	--	--	--	--	--	X	--	--	--	--	--
2.2.4.4.3.2	Integrated Solar Array	--	--	X	--	--	--	--	--	X	--	--	--	--	--
2.2.4.4.3.3	Integrated Communications Tx/Rx Antenna	--	--	X	--	--	--	--	--	X	--	--	--	--	--
2.2.4.4.4	Printed Protoflight	--	--	X	--	--	--	--	--	X	--	--	--	--	--
2.2.4.4.5	Printed On-Orbit	--	--	--	--	--	--	--	--	--	--	--	--	--	--
2.2.4.5	Ground/Flight Test Equipment Plan	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.2.5	Technology Demonstration Plan	--	1	2	3	X	--	--	4	5	6	X	--	--	X
2.2.5.1	Characterize Radiant Energy Beam	--	--	--	--	--	--	X	--	--	--	--	--	X	--
2.2.5.2	Optimize Radiant Energy Beam	--	--	--	--	--	--	X	--	--	--	--	--	X	--
2.2.5.3	Operate Radiant Energy Beam	--	--	--	--	--	--	X	--	--	--	--	--	X	--
2.2.5.4	Near Field/Far Field Test Bed	--	--	--	--	--	--	X	--	--	--	--	--	X	--
2.2.5.5	Loosely Coupled Modular Structures Test Bed	--	--	--	--	--	--	X	--	--	--	--	--	X	--
2.2.5.6	Propulsion Augment Testbed	--	--	--	--	--	--	X	--	--	--	--	--	X	--
2.2.5.7	Platform Infrastructure Technology Testbed	--	--	--	--	--	--	X	--	--	--	--	--	X	--
2.2.5.8	Reflectarray Rectennas	--	--	--	--	--	--	X	--	--	--	--	--	X	--
2.2.5.9	Alpha CubeSat Mission	--	--	--	--	--	--	--	--	--	--	--	--	X	--
2.2.6	Technology Deployment Plan	--	1	2	3	X	--	--	4	5	6	X	--	--	X
2.2.6.1	Asteroidal Assay Mission	--	--	--	--	--	--	X	--	--	--	--	--	X	--

WBS #	WBS Element Name	Kick-Off	MDR-I	PDR-I	CDR-I	FRR-I	Launch-I	FOP-I	MDR-II	PDR-II	CDR-II	FRR-II	Launch-II	FOP-II	FPR
2.2.6.2	Co-orbiting Manufacturing Cell Mission	--	--	--	--	--	--	X	--	--	--	--	--	X	--
2.2.6.3	Beyond Earth Orbit Deployment Platform	--	--	--	--	--	--	X	--	--	--	--	--	X	--
2.3	Systems Analysis														
2.3.1	Training Products and Procedures	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.3.2	Safety Review Packages	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.3.3	Hardware Verification Data	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.3.4	Software Verification Data	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.3.5	Investigator Participation Real-Time Plan	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.3.6	Crew Conference Plan	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.3.7	Anomaly Resolution Plan	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.3.8	Data Collection and Return Plan	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.3.9	Flight Test Article Recovery & Reuse Plan	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.3.10	System Assembly and Servicing On-orbit	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.4	Development Interfaces	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.5	Demonstration Interfaces	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.6	Deployment Interfaces	--	1	2	3	X	--	--	4	5	6	X	--	--	--
2.7	Technical Risk Management	1	2	3	4	5	--	--	6	7	8	9	--	--	X
2.8	Verification & Validation Plan	1	2	3	4	5	--	--	6	7	8	9	--	--	X
2.9	Engineering Reviews	--	X	X	X	X	--	--	X	X	X	X	--	--	--
3	**Satellite Bus - Detailed Design and Construction**														
3.1	Structures & Mechanical Systems (S&M)	--	1	2	3	X	--	--	4	5	6	X	--	--	X
3.2	Electrical Power System (EPS)	--	1	2	3	X	--	--	4	5	6	X	--	--	X
3.3	Data Management System (DMS)	--	1	2	3	X	--	--	4	5	6	X	--	--	X
3.4	GN&C/ACS	--	1	2	3	X	--	--	4	5	6	X	--	--	X
3.5	Thermal Control System(TCS)	--	1	2	3	X	--	--	4	5	6	X	--	--	X
3.6	Communications System (COMM)	--	1	2	3	X	--	--	4	5	6	X	--	--	X
3.7	Propulsion System (PROP)	--	1	2	3	X	--	--	4	5	6	X	--	--	X
4	**Transmitter - Detailed Design and Construction**														
4.1	Existing ISS Ka Band Infrastructure	--	X	--	--	--	--	--	--	--	--	--	--	--	--
4.2	Optimized Ka Band Transmitter, Protoflight	--	--	--	--	X	--	--	--	--	--	--	--	--	--
4.3	Optimized W Band Transmitter, Protoflight	--	--	--	--	--	--	--	--	--	--	X	--	--	--
4.4	Optimized Other Transmitter, Protoflight (scar)	--	1	--	--	--	--	--	2	--	--	--	--	--	3
5	**Rectenna - Detailed Design and Construction**														
5.1	Ka Band Optimized Rectenna, Protoflight	--	--	--	--	X	--	--	--	--	--	--	--	--	X
5.2	W Band Optimized Rectenna, Protoflight	--	--	--	--	--	--	--	--	--	--	X	--	--	X
5.3	Reflectarray Integration	--	--	--	--	X	--	--	--	--	--	X	--	--	X
5.4	Data Capture & Analysis System	--	1	2	3	X	--	--	4	5	6	X	--	--	X
5.5	Printed Protoflight Rectenna	--	--	--	--	X	--	--	--	--	--	--	--	--	X
5.6	Printed On-Orbit Rectenna	--	--	--	--	--	--	--	--	--	--	X	--	--	X
6	**Integration, Verification & Validation**														
6.1	Bus Ground Test	--	1	2	3	X	--	--	4	5	6	X	--	--	X
6.2	Payload (Rectenna) Ground Test	--	1	2	3	X	--	--	4	5	6	X	--	--	X
6.3	Temperature/Vacuum Testing	--	1	2	3	X	--	--	4	5	6	X	--	--	X
6.4	RFI Ground Test	--	1	2	3	X	--	--	4	5	6	X	--	--	X
6.5	Bus/Payload Integration	--	1	2	3	X	--	--	4	5	6	X	--	--	X
6.6	GN&C/ACS Validation	--	1	2	3	X	--	--	4	5	6	X	--	--	X
6.7	On Orbit Test	--	1	2	3	4	--	X	5	6	7	8	--	X	X
7	Launch Accommodation														
7.1	Cargo Integration	--	1	2	3	X	--	--	4	5	6	X	--	--	X
7.2	ISS Integration	--	1	2	3	X	--	--	4	5	6	X	--	--	X
7.3	ISS Support	--	1	2	3	X	--	--	4	5	6	X	--	--	X
7.4	JEM EF Allocation	--	1	2	3	X	--	--	4	5	6	X	--	--	X
7.5	EVR Allocation	--	1	2	3	X	--	--	4	5	6	X	--	--	X
7.6	ISS GN&C Interface	--	1	2	3	X	--	--	4	5	6	X	--	--	X
8	Operations														
8.1	Management Operations Control Applications	--	1	2	3	X	--	--	4	5	6	X	--	--	X
8.2	Ground Segment - Communications	--	1	2	3	X	--	--	4	5	6	X	--	--	X
8.3	Development Operations	--	1	2	3	X	--	--	4	5	6	X	--	--	X
8.4	Demonstration Operations	--	1	2	3	X	--	--	4	5	6	X	--	--	X
8.5	Deployment Operations	--	1	2	3	X	--	--	4	5	6	X	--	--	X

Notes:
(1) Anticipated mission schedule is 24 months from availability of funding.
(2) The term "Plan" is deemed inclusive of the definition, approval, implementation, testing, and verification of the subject work item.
(3) A numerical entry indicates a plan revision level. An "X" indicates a required completion of a work item for a given phase or the Final Project Report
(4) See narrative text for nomeclature key.

Xtraordinary Innovative Space Partnerships, Inc. (XISP-Inc) ISS Power Beaming Mission Work Breakdown Structure – January 20, 2017 Revision A



Perceived Impact

As noted in the Reference and Citations section the work of William Brown and others [1-6] clearly indicates that Space-to-Space Power Beaming holds national and international promise yet there are no civilian (or known military) applications extant. This work is applied engineering, not new fundamental physics. It combines a technology development push (i.e., testbed) and multiple instances of mission requirements pull (i.e., deployment) to yield cost effective demonstrations which extend the state of the art.

This TD^3 mission combines include:

- stranded intellectual property from other technology development efforts,
- novel systems engineering based on the applicable general problems in the domain(s) of interest,
- an understanding of how to draw out commercial requirements that can be monetized, as well as an understanding of mission enhancing and mission enabling technology from a flight projects perspective -- to yield systems which are demonstrably useful for one or more missions for each increment of resources invested.

Relevance of the Work

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.

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. multiple spacecraft (e.g., fractionated spacecraft, interferometric groups, swarms)
    b. large 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.
6) Potential backup systems for the above uses.

Mitigating risks by providing SSPB as a utility can yield more missions and more successful ones.

Data Sharing Plan

XISP-Inc on behalf of the proposed Consortium commits to document the mission development, demonstration, and deployment efforts, by submitting abstracts for technical papers and presentations (preparing and presenting as applicable) at the following fora:

- ISS R&D Conference **2013, 2014, 2015, 2016**, 2017, 2018, and 2019.
- ISDC **2013, 2014, 2015, 2016**, 2017, 2018, and 2019.
- IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE) **2013, 2015,** 2017, 2018, and 2019.
- AIAA Space **2016**, 2017, 2018, and 2019.
- International Astronautical Congress (IAC) **2014, 2016**, 2017, 2018, and 2019.

XISP-Inc has provided presentations and/or papers in related to the Space-to-Space Power Beaming mission in all of the bolded years in the reoccurring fora indicated above and multiple other conferences as noted in the references section.

ISS Requirements

The anticipated ISS requirements of the SSPB mission are:

- Satellite Bus & Rectenna
  - Up Mass: 14 Kg [TBD – ROM from Alpha CubeSat]
  - Volume: ~10,702 cm^3 = .107 m^3 [TBD – ROM from Alpha CubeSat]
  - Power: ~5 W to less ~100 W [TBD – ROM from Alpha CubeSat]
  - Data: 1 Mbps or less (command, control, tracking, telemetry, and payload)
  - Equipment: commercial pressurized cargo manifest, on-orbit pressurized stowage, JEM Exposed Facility Airlock, CYCLOPS, JEM RMS, MSC (MT,MBS,SSRMS,SPDM)
  - Crew Time: unload cargo carrier & stow, unpack, final assembly, CYCLOPS integration, and airlock operation. ~1 to 2 hours. Change out of reflectarray rectenna if applicable is estimated to be ~1 to 2 hours. Standby supervision during experiment operations.

- W band optimized transmitter
  - Up Mass: 362 Kg or less [TBD, ROM from SCaN Testbed & ISC-EF]
    - JEM Kibo Exposed Facility constraint 500 Kg maximum
  - Volume: 1.5 m^3 or less
    - JEM Kibo Exposed Facility constraint 1.5 m^3 maximum
  - Power: 3 Kw or less per power port (mission baseline is one power port)
    - JEM Kibo Exposed Facility constraint 3 Kw maximum per power port
    - JEM Kibo Exposed Facility constraint one or two power ports
      - It is understood that the dual port capability has not been used to date and may not be available
  - Data: 1 Mbps or less
    - JEM Kibo Exposed Facility data requirement will be de minimis if an alternate return channel is used

- JEM Kibo Exposed Facility constraint Low-rate (MIL-STD-1553) 1 Mbps
- JEM Kibo Exposed Facility constraint High-rate (Shared Ethernet 100 Base-TX) 43 Mbps
- ISS Gigabit Network: Access requested, TBD availability
- ISS Wi-Fi Network: Access requested, TBD availability

- Equipment: commercial unpressurized cargo manifest, on-orbit unpressurized stowage, JEM RMS, MSC (MT,MBS,SSRMS,SPDM)
- Crew Time: unload cargo carrier & stow, unpack, installation. ~1 hours (primary EVR operations teleoperated from the ground). Standby supervision during experiment operations.