CHALLENGES OF SPACE POWER BEAMING: FORGING PRODUCTION SERVICES FROM THE TECHNOLOGY DEVELOPMENT TRADE SPACE

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Abstract

This paper and presentation is intended to address the challenges of power beaming from the perspective of a focused incremental Technology Development, Demonstration, and Deployment (TD^3) mission for Space-to-Space Power Beaming (SSPB) to be implemented as a commercial International Space Station (ISS) TD^3 mission. The SSPB mission builds on foundational research in the field and mission development work accomplished to date by XISP-Inc. The SSPB mission is intended to help mitigate cost, schedule, and technical risk associated with the short-, mid-, and long-term application of space power and ancillary services (e.g., data, communications, navigation, time, etc.) beaming technology. This mission involves significant technology development, demonstration, and deployment elements, orchestrated and implemented in a manner that delivers significant value to a number of customers co-orbiting with the ISS, and will serve as a testbed environment for more expansive SSPB TD^3 efforts. The latest estimated deliverable power-density and power-received values based on the collection efficiency calculations (which have been correlated to ground tests by other researchers) provide a compelling comparison between estimated delivered power density and the Solar Constant for the orbital distance of immediate interest. The calculated values clearly show that the low end of the Ka band (i.e., 26.5 GHz shown), with a delivered power density an order of magnitude less than the Solar Constant, is very benign. The high end of the Ka band (i.e., 36 GHz shown) can actually meet some customer requirements, though at best at a small multiple of the Solar Constant. However, the W band (i.e., 95 GHz) can provide a power density an order of magnitude or higher than the Solar Constant. The challenge in all instances is engineering systems with an end-to-end efficiency which is satisfactory and sufficient for the application. The ability to provide power when and where needed is essential to virtually all aspects of human endeavour, and is enabling for any form of space development/settlement. Space solar power technology holds the promise of being one of the few large-scale energy generation options that can scale to meet the growing electrical energy demand in space. This mission is a unique opportunity to foster the development of SSPB by leveraging ground based piecewise testing and ISS resources to create an integrated SSPB testbed environment on and near the ISS that supports the development of frequency-agnostic-radiant-energy beaming technology.

Keywords: Space-to-Space Power Beaming Wireless Ancillary Services

Nomenclature

A_t = Area of transmitting antenna, cm^2
AU = Astronomical Unit, average distance between the Earth and the Sun
I_{sc} = Solar Constant at 1 AU, $Watts/cm^2$
P_d = Power Density, $Watts/cm^2$
P_t = Power input, Watts

Acronyms/Abbreviations

Technology Development, Demonstration, and Deployment (TD^3)

1. Introduction

A focused incremental Technology Development, Demonstration, and Deployment (TD^3) mission for Space-to-Space Power Beaming (SSPB) is moving forward with the advice and consent of NASA as a commercial International Space Station (ISS) TD^3 mission. The SSPB mission builds on foundational research in the field, relatable applications research performed by the SSPB mission consortium participants, and mission development work accomplished to date by XISP-Inc.[1-9] The SSPB mission is intended to help mitigate cost, schedule, and technical risk associated with the short-, mid-, and long-term application of space power and ancillary services (e.g., data, communications, navigation, time, etc.) beaming technology. This mission involves significant technology development, demonstration, and deployment elements, orchestrated and implemented in a manner that delivers significant value to a number of customers co-orbiting with the ISS, and will serve as a testbed environment for more expansive SSPB TD^3 efforts.

The first phase (Phase I) of the SSPB mission is technology development. This includes lab/ground test work (XISP-Inc & teammate Internal Research and Development (IRaD) and leverageable contract research & development) which will transition into highly configurable space-qualified instances of Software Defined Radio (SDR) transceivers, rectennas, and related control systems. These elements will have mutable/switchable apertures (frequency-agnostic radiant energy beaming source), separate and converged conformal rectenna/solar array/antenna constructs that are configurable/tuneable (combination of phased array, reflectarray, and multi-layer/junction, and related technologies), and software-driven controls. The elements will be integrated to form an on-orbit testbed consisting of an ISS-based transceiver, a co-orbiting CubeSat flight test article, and related management operations control applications as shown in Figure 1 - SSPB Overview. The testbed will support the near–real-time characterization, optimization, and operationalization of an unbundled power and ancillary services beaming system.

The latest estimated deliverable power-density and power-received values based on the collection efficiency calculations (which have been correlated to ground tests by other researchers) provide a compelling comparison between estimated delivered power density and the Solar Constant for the orbital distance of immediate interest. The calculated values clearly show that the low end of the Ka band (i.e., 26.5 GHz shown), with a delivered power density an order of magnitude less than the Solar Constant, is very benign. The high end of the Ka band (i.e., 36 GHz shown) can actually meet some customer requirements, though at best at a small multiple of the Solar Constant. However, the W band (i.e., 95 GHz) can provide a power density an order of magnitude or higher than the Solar Constant, as shown in Table 1 – Comparing Beaming Power Density and the Solar Constant.

The challenge in all instances is engineering systems with an end-to-end efficiency which is satisfactory and sufficient for the application. The ability to provide power when and where needed is essential to virtually all aspects of human endeavour, and is enabling for any form of space development/settlement. Space solar power technology holds the promise of being one of the few large-scale energy generation options that can scale to meet the growing electrical energy demand in space.

This mission is a unique opportunity to foster the development of SSPB by leveraging ground based piecewise testing and ISS resources to create an integrated SSPB testbed environment on and near the ISS that supports the development of frequency-agnostic-radiant-energy beaming technology. Use of the ISS significantly reduces the cost and complexity of the proposed mission. The total estimated time to complete Phase I is 16 months, with a budget estimate (both cash and in-kind) of approximately $7 million. Of this budget, $250 thousand is requested CASIS mission development funding plus CASIS integration partner costs. XISP has received conditional letters of support from capital funding sources committed to provide the balance if support from CASIS gives the SSPB mission recognizable standing.

2. Detailed Project Plan

The mission development effort for a TD^3 mission, in the absence of the large scale financial backing required for unilateral action, is a multi-step process that begins with identifying the stakeholders for a particular problem space, the intellectual property and other resources that they can bring to the table, what they perceive as public domain, and the outlines of the solution space that constitute the potential their confluence of interests. This process is outlined in Figure 2 – XISP-Inc "Follow The Resources" Mission Development Diagram. The mission development process is both iterative and recursive. It requires the definition, codification, and orchestration of both technology development "push" and mission requirements "pull".

2.1 Research Questions & Significance

XISP-Inc has hypothesized that disaggregated (unbundled) power systems (i.e., the separation of power generation, transmission, distribution, and loads) can reduce spacecraft complexity, mass, and volume, thereby reducing the cost, schedule, and technical risk of a given mission. SSPB can also foster the development of loosely coupled modular structures to enable:

- Formation flying of multiple spacecraft (e.g., interferometric groups, swarms)
- 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.

The SSPB mission objective is to test the hypothesis by creating a viable design for a Space-to-Space Power System that is cost-effective, scalable, and readily extensible to multiple applications. The SSPB mission phases will result in a significant advancement of the technology's maturation from TRL 4 to 8/9. Such SSPB systems must accommodate key service variables for which the optimization varies with each addressable market:

- Frequency/Wavelength (microwave to eye-safe optical),
- Distance (near field, boundary regions, far field),

- Magnitude (i.e. power level supporting non-weaponization and peaceful use [individual end-user scale <10 kW, industrial scale 10 kW to 100 kW, military scale > 100 kW]),
- Duration (pulsed, scheduled, continuous),
- Availability (on demand, scheduled, prioritized, by exception),
- Security (misuse, interruption, destruction), and
- Performance (net transfer, end-to-end efficiency, piecewise efficiency, effective difference).

2.2 What is the 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, or communication equipment). State-of-the-art beamed power systems for space applications are at TRL 4. This work will develop the first Space-to-Space radiant energy beaming testbed to support the characterization, optimization, and operationalization of space solar power radiant energy beaming technology and the proposed follow-on demonstration will be the first-ever commercial system test of in-space beamed power, advancing this technology to TRL 8/9. This includes the development and in situ verification of the following:

- Near–real-time state models of the radiant energy beam components,
- Beam forming characteristics and 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, and operational rules for deployment will also be tested and verified.

Table 2 outlines the proposed SSPB mission innovations and benefits compared to the current state of the art.

2.3 Why the ISS or other Particular Venue?

The SSPB mission needs all components of an end-to-end power system in space in order to accomplish the mission objectives. More specifically, it requires:

- A source of readily available power (ISS Power System),
- A stable platform for mounting and operating a transmitter (ISS JEM Exposed Facility) with a clear view facing RAM, starboard with a zenith bias,
- Persistent exposure to the low Earth orbit environment (e.g., vacuum, atomic oxygen, radiation, debris, hot/cold cycling, and microgravity) duplicating the actual intended operational environment (ISS environment).
- All of the above, to provide a suitable vantage point for an aerospace testbed for TRL-raising applications for space solar power technologies.
- The ISS serves as a proof-of-concept platform for evaluating the potential for building and operating a space-based power and ancillary services utility, and
- The ISS reduces the cost and complexity of SSPB missions and the resulting infrastructure enables routine use of ISS co-orbiting free-flying spacecraft.

2.4 What is the Related Work?

The references section of this paper contains an extensive set of prior work references that serve as technical foundation for this work, as well as including the Principal Investigator’s selected publications, presentations, papers and collaborations with other space solar power experts. The SSPB mission development effort has made extensive use of professional community fora to critique and evolve the mission. Since 2005, the proposed SSPB Principal Investigator Gary Barnhard has written and presented over 56 related technical papers and/or presentations germane to the proposed SSPB mission to a wide range of professional fora related to space solar power, ancillary services (i.e., communications, data, and navigation/time) and the evolution of proposed TD^3 missions.

2.5 What is the Timeline and Success Criteria?

The proposed SSPB mission milestone schedule is shown in Table 2 – XISP-Inc SSPB Phase I, II, and III Milestone Schedule. The top level success criterion is the accomplishment of the milestones listed. More specifically, the mission shall:

a. Complete the Mission Development, detailed design, and make/buy parts out of the SSPB mission components.
b. Complete the Form, Fit & Function Ground Test and analysis for the SSPB mission components.
c. Complete the Protoflight Ground Test and analysis for the SSPB mission components.
d. Complete the final build and deliver of the SSPB mission components for launch integration.
e. Achieve successful launch and delivery of the SSPB mission components as commercial cargo to the ISS.
f. Complete the installation and integration of the SSPB mission components with the ISS.
g. Activate the SSPB testbed and repeatedly exercise the ability to provide a near–real-time characterization of the radiant energy beam and the end-to-end system, capturing all relevant performance, availability, and security data.

h. Repeatedly exercise the ability to optimize the radiant energy beam to tune the piecewise efficiency of the beam and the end-to-end system, capturing all relevant performance, availability, and security data.
i. Repeatedly document the ability to operate the SSPB testbed in full conformance with prevailing ISS operational rules, procedures, and guidelines.

Demonstrate the use of the testbed to deliver power and ancillary services to a payload deployed on the SSPB co-orbiting small satellite flight test article.

2.6 What is the Risk Mitigation Strategy?

Every TD^3 mission has one or more significant areas of cost, schedule or technical risk which must be identified, assessed and some form of mitigation strategy implemented. The main risks to the SSPB mission arise if the new flight components (as described in the Operational Approach Section) are not successfully built, deployed or operated. Additional risk have been identified and have been grouped by the applicable primary hardware / software elements.

2.6.1 ISS Transceiver & Apertures

The successful activation of deployable apertures with a total surface area of one square meter or less is well within the operational envelope of previously installed ISS systems. The risks associated with the activation and operation of the transceiver are expected to be mitigated by high fidelity ground testing/modelling.

2.6.2 Satellite Bus/Subsystems

Activation and control of the satellite bus and its proximity to ISS poses a risk. The activation risk is the satellite bus will be deployed RAM, Starboard or Port, with a Zenith bias with an initial non-zero velocity, the system must activate to assume a station-keeping position co-orbiting with the ISS just outside the Keep Out Sphere of 200 m. The control risk is the need to accommodate ISS Attitude Control System adjustments on an as needed basis. The proximity risk is given that ISS is constantly losing altitude except during reboost manoeuvres, regardless of the operational state of the satellite bus after its deployment, the ISS will be in no danger of colliding with it. The mitigation of these risks requires a two fault tolerant activation and control system and sufficient propellant reserves. The resulting dwell time for an ISS-based beam would be limited by the ability of the satellite bus active Attitude Control System/Propulsion system to maintain position.

2.6.3 Rectenna

The ability to produce a rectenna with optimized performance for the full range of frequencies of interest is a significant area of technical, schedule, and cost risk. It is anticipated that the mitigation strategy will be to accept a satisfactory and sufficient design bounded by experiment (i.e., be frequency agnostic within certain defined limits) rather than force the optimization to a specific frequency from the start of the mission that could inadvertently overshoot or undershoot what is achievable.

2.6.4 Radiant Energy Beaming Control and Safety Interlock System

This system will use the XISP-Inc Management Operations Control Applications (MOCA) – (XISP Xlink near–real-time state model extended NASA ARC Mission Control Technologies OpenMCT software suite), and an IPv6 Delay/Disruption Tolerant Networking (DTN)-enabled implementation of WAVElan SECurity using IPsec (WAVESEC) compatible with the Immortal Data Inc. Shipslog Data Capture and Analysis system. Unless the WAVESEC link is established, authorized, and validated, outbound transmitter power will be inhibited to a minimum sensible level. This technology has been used in other terrestrial applications, but use for SSPB is a novel application. The mitigation for this is additional crew and/or ground control time associated with the actuation of additional manual inhibits.

2.7 What is the Operational Approach?

This XISP-Inc SSPB mission concept of operations is summarized in Figure 3. The proposal and the operational concept are focused on the Phase I technology development phase:

- ISS transceiver transportation and location initially on the Bartolomeo exposed facility as ram facing double payload. The transceiver package will include the necessary JEM EF interfaces for use in subsequent Phases.
- Satellite Bus (6U CubeSat Flight Test Article) transportation to ISS and release into ram-starboard position with zenith bias relative to ISS
- Demonstration of radiant energy beaming between transceiver and 6U CubeSat. The CubeSat will be outside the 200m ISS spherical zone of exclusion and at a maximum distance of 1 km during testbed operations.

The space-based hardware, design and operation and are further described in detail in the following sections.

2.7.1 ISS Transceiver

Illustrations of the proposed ISS transceiver are shown in Figure 4. The baseline ISS transceiver is an evolved Raytheon IRaD product to be infused with the Tethers Unlimited, Inc. Swift SDR enhancements which include waveform library & electronics slice adjustments to suit bi-directional multiplexing, retro-direction, and compliance with ISS Electromagnetic interference (EMI), electromagnetic compatibility (EMC), and Electromagnetic Environmental Effects (EME) requirements. The ISS transceiver will be similar to the AFRL/Raytheon 95 GHz phased array antenna aperture and will fit within the JEM Exposed Facility Payload Carrier envelope. The design incorporates all required EVR, JEM Exposed Facility, and Columbus Bartolomeo (Barto) interfaces. The transceiver will be launched to ISS as an unpressurized cargo item in the SpaceX Dragon "Trunk" (or a JAXA HTV-X) with payload removal by the MSC and hand off as needed to allow installation on the JEM Exposed Facility. This is now a routine EVA Robotics (EVR) operation. A summary of the SSPB mission payload accommodation requirements is shown in Table 4.

- The combined mass of the transceiver and the payload carrier with required interfaces will be less than or equal to 450 kg.
- The total volume of the transceiver and the payload carrier with required interfaces will be less than or equal to ~1.44 m3 (1m x 1.8m x .8m).
- The maximum input power drawn if the use of one Remote Power Controller is authorized will be up to 3 kW, 113-128 VDC on a scheduled basis. The estimated actual power draw for testbed operations based on anticipated efficiencies and the thermal limitations of the 6U CubeSat flight test article is less than 300 W. The duration and frequency of operation will be dynamically schedulable based on power availability.
- For Phase II/III operations the maximum input power draw if the use of two Remote Power Controllers is authorized could be up to 6 kW, 113-128 VDC on a scheduled basis. The duration and frequency of operation will be dynamically schedulable based on power availability.
- A low-rate data connection to the 1 Mbps (MIL-STD-1553) bus will be available.
- A high-rate data connection to the 43 Mbps (shared) Ethernet 100 Base-TX and gigabit Ethernet payload networks will also be supported by the SSPB transceiver payload for interfacing with available networks.
- A high-rate data connection to one or more wireless networks will also be supported by the SSPB transceiver payload for interfacing with available networks.

The transceiver with one or more deployable apertures with a surface area of one square meter or less will be electrically and mechanically inert until successfully attached to the EF utility port and the utility port power/data connections are activated. This is well within the operational envelope of previously installed ISS systems. Since the EMI/EMC requirements mandate full conformance with prevailing ISS rules, procedures, and guidelines, any risk associated with the operation of the transceiver will have already been dispositioned by ground test and analysis. Given that all transmissions will be away from the ISS towards unobstructed space, no unique risks are imposed with operation of this component.

While there are multiple other sources for the ISS transceiver, Raytheon is an extraordinarily compelling choice as the company is a pioneer and leader in microwave technology and have granted XISP access to their intellectual property. Raytheon is a committed and active member of the SSPB Mission Consortium.

2.7.2 Satellite Bus (6U CubeSat Flight Test Article)

The XISP non-toxic satellite bus will be similar in design to the Alpha Cube Sat (ACS) PDR design shown in Figure 5. The satellite bus is Extra Vehicular Robotic (EVR) deployable, with H2O-based active Attitude Control System/Propulsion thrusters, integrated with SDR including a task-appropriate waveform library and multiplexing capabilities, and will use reflectarray solar array/rectennas. Its total surface area is less than one square meter. The satellite bus will be launched as soft packed pressurized cargo preloaded into an EVR compatible Planetary Resources standard deployment container. The container will be integrated with the NanoRacks, Inc. Kaber EVR interface on-orbit by the ISS crew and deployed through the JAXA Kibo lab airlock. EVR resources (JEM RMS and/or MSC) will be used to relocate and deploy the satellite bus under ground control.

- The baseline Satellite Bus is the Blue Canyon Technologies XB Spacecraft.
- The flight test article will be an instance of the Alpha Cube Sat design, constructed from the vendor's COTS flight qualified systems/subsystems with the following exceptions/modifications:
  - o Rectenna overlay, a separately developed item supplied* by Raytheon, Inc.
  - o SDR Transceiver - Communications System supplied* by Tethers Unlimited, Inc.
  - o H20 Thruster - Propulsion System supplied* by Deep Space Industries, Inc.
  - o Data Capture & Analysis Subsystem supplied* by Immortal Data, Inc.

(*Technical, cost, and/or schedule considerations could alter the anticipated suppliers.)

- While there are multiple other satellite bus alternatives that have been identified as technology, cost, and schedule risk mitigation measures, Blue Canyon

Technologies' industry leading product and supporting systems/subsystems, commitment to be an active part of the SSPB Mission Consortium and demonstrated commitment to space development makes them a compelling choice.

- The mass of the 6U Satellite Bus portion with a full complement of systems/subsystems, including an integrated deployable reflectarray solar array/antenna/rectenna, is approximately ~14 kg.
- The total mass of the flight test article integrated with flight support equipment is ~40 kg, assuming the use of a Planetary Resources deployment canister with the integrated satellite installed on the ground.
- The deployment canister will be wrapped in bubble pack, surrounded by foam and stowed in a standard soft pack cargo bag for launch in a pressurized logistic carrier to the ISS.

2.7.3 SDR Transceiver – Communications System

The baseline SDR Transceiver – Communications System for satellite bus is the Tethers Unlimited, Inc. Swift SDR. While there are several other COTS SDR alternatives that have been identified as technology, cost, and schedule risk mitigation measures, Tethers Unlimited, Inc.'s industry leading product, commitment to be an active part of the SSPB Mission Consortium and demonstrated commitment to space development makes them a compelling choice.

2.7.4 H_2O Thruster – Propulsion System

The baseline H_20 Thruster - Propulsion System – for the technology development flight test article is the Deep Space Industries, Inc. Comet H_2O thruster/propulsion system. While there are several other H_20 Thruster - Propulsion System alternatives that have been identified as technology, cost, and schedule risk mitigation measures, Deep Space Industries, Inc.'s industry leading product, commitment to be an active part of the SSPB Mission Consortium and demonstrated commitment to space development makes them a compelling choice.

2.7.5 Baseline Rectenna

The baseline rectenna for the technology development flight test article is an evolved Raytheon IRaD product to be infused with the SSPB Mission Consortium derived technology enhancements. Secondary supporting vendors and university researchers have been identified and engaged as technology, cost, and schedule risk mitigation measures to allow for the parsimonious use of Raytheon resources.

2.7.6 Data Capture & Analysis System – Data System Overlay

- The baseline Data Capture & Analysis System – Data System Overlay – for the technology development flight test article is the Immortal Data, Inc. Shipslog product line.
- Data collection will be performed by a customized implementation of the Immortal Data Shipslog Suite with headless elements attached to the ISS payload network via wired, Wi-Fi (802.11 AC), and/or RF (direct or relayed) connections. This will address data collection from the ISS transmitter, the active ISS payload workstation, the deployed 6U CubeSat for testbed operations, and the ISS reference time & telemetry markers.
- This system includes all the necessary sensors, augmented processing as well as storage capability, and bus control logic to ensure all generated data is captured and made available for both near real-time analysis and extended analysis on the ground.
- A near–real-time state model of the SSPB testbed will run continuously on mission-provided resources. The model will be served up as a web page available on demand to any workstation on the ISS payload network for ISS observation, monitoring, and control, and will be made available to support ground observation, monitoring, and control.
- This work will require the implementation of Management Operations Control Applications supporting interfaces with the Flight Test Article Satellite Bus Data System, the Flight Test Article Rectenna, the ISS Transceiver, an ISS Payload Network laptop, as well as virtual interfaces with the ISS Payload Network, ISS Flight Operations Center, ISS Payload Operations Center, and the XISP-Inc Remote Payload Operations Center.
- While there are multiple other vendor alternatives that have been identified as technology, cost, and schedule risk mitigation measures, Immortal Data Inc.'s evolving industry challenging product line, active role in XISP-Inc mission development, commitment to be an active part of the SSPB Mission Consortium, and demonstrated commitment to space development makes them a compelling choice.

2.8 Hardware Development Timelines

Vendor-quoted timelines for the SSPB Mission Phase 1 Commercial-Off-The-Shelf (COTS) components are less than 3 months for test hardware and less than 6 months for delivery of the flight hardware components.
The work on the customized components will start by establishing a baseline of what is currently available and known to function from SSPB Mission Consortium members. In addition, a set of proposed enhancements for each component will be identified to increase the performance that can be developed with an acceptable level of cost, schedule, and technical risk (i.e., from vendors with existing pro33duct, vendors/labs with analogous product, and vendors/labs with potentially

viable prototypes). A “bake off” will be defined and kicked off in the beginning of the next phase of mission development, and will culminate in final selections being made based on the testing results at the end of the Mission Development Phase. It is anticipated that the competitive process could take up to 6 months, and the delivery of the customized components could take up to an additional 6 months. While the timeline for the production of the customized components can be decreased to perhaps as short as 3 months total, it is anticipated that achieved performance will be improved by a period of focused technology development.

2.7.1 Satellite Bus /Subsystems

Using a combination of the XISP-Inc Alpha Cube Sat preliminary design (see Table 12 -- SSPB Mission WBS Element Technology Readiness Level) and the integration of lightly tweaked COTS components, it is anticipated that procurement of the required flight test article will be a tractable task. The verification approach will be by similarity and test. COTS detailed schematics and engineering drawings are available for the Satellite Bus and all subsystems.

2.7.2 Rectenna

The successful development of a deployable reflectarray solar array/rectennas attachable to a 6U CubeSat with active attitude control and H_2O propulsion, having a total surface area of one square meter or less, while challenging is not intractable given sufficient high fidelity ground testing/modelling. However, experiments will have to be conducted to determine how far up the available frequency spectrum it is possible to go while still retaining acceptable conversion efficiency. The ability to produce a functional rectenna is not at issue, but optimizing the performance is. The ability to produce an optimized rectenna to purpose is a significant area of technical, schedule, and cost risk. To mitigate this risk, the SSPB mission will be frequency agnostic with the intention to accept a satisfactory and sufficient rectenna design bounded by an experimental “bake-off,” rather than forcing optimization to a specific frequency from the start. This work will leverage the extant high frequency rectenna design work accomplished by Raytheon as the baseline design.

2.7.3 ISS Transceiver

The successful development of an EVR deployable unpressurized ISS Transceiver payload compatible with both the Columbus Bartolomeo exposed facility and the JEM Exposed Facility is the SSPB mission baseline and has no identified technical issues. The accommodation of the gimballed phase array aperture having a total surface area of less than one square meter and the necessary transceiver electronics, while challenging is not intractable given sufficient high fidelity ground testing/modelling. However, experiments will have to be conducted to determine how far up the available frequency spectrum it is possible to go while still retaining acceptable conversion efficiency. The ability to produce a functional transceiver is not at issue, but optimizing the performance is. The ability to produce an optimized transceiver to purpose is a significant area of technical, schedule, and cost risk. To mitigate this risk, the SSPB mission will be frequency agnostic with the intention to accept a satisfactory and sufficient transceiver design bounded by an experimental “bake-off,” rather than forcing optimization to a specific frequency from the start. This work will leverage the extant high frequency transceiver design work accomplished by Raytheon as the baseline design.

2.8 Software Development Timelines

- The Satellite Bus (containing multiple systems/subsystems) software comes pre-integrated with the satellite bus system, which includes a user-programmable and extensible avionics/data system,
- The Software Defined Radio (SDR) Transceiver for the Satellite Bus, which forms the Communications System, comes with predefined wave form libraries and/or electronics slices to support desired frequencies as well as the necessary code for operational use,
- The H20 Thruster - Propulsion System includes an Applications Programming Interface (API) for interfacing with the Guidance, Navigation, and Control (GN&C) System/Satellite Bus Avionics,
- The Data Capture & Analysis System - Data System Overlay includes an API for making the necessary connections to interface with all SSPB mission components,
- The baseline rectenna, while a source of data, is not anticipated to be programmable. However, certain rectenna enhancements may be implemented that could alter this assumption.
- Both the ISS and satellite bus transceivers are subject to the inclusion of software and in some cases hardware enhancements to increase end-to-end system performance.

In addition, XISP will contribute the tools for building:

2.8.1 Near real-time state model/control capability

This will permit the characterization, optimization, and codified compliance with operational rules of the radiant energy beaming testbed, the demonstration system, and the infrastructure deployment system.

2.8.2 Radiant energy beaming control and safety interlock

This system will make use of the XISP-Inc MOCA – (XISP Xlink near–real-time state model extended NASA ARC Mission Control Technologies

OpenMCT software suite), and an IPv6 Delay/Disruption Tolerant Networking (DTN) enabled implementation of WAVElan SECurity using IPsec (WAVESEC) compatible with the Immortal Data Inc. Shipslog Data Capture and Analysis system.

2.8.3 Other Software/Ancillary Utility Related Components

The ability to accommodate power, data, communications, navigation, and time multiplexing within radiant energy beams is not anticipated to be materially different from existing terrestrial and space multiplexing tasks. The ISS Space Communications and Navigation (SCaN) Test Bed has demonstrated the use of a library of Software Defined Radio waveforms on orbit. The addition of power and ancillary services waveforms in the library of a Software Defined Radio (SDR) is anticipated to be just another instance of a well-defined process.

2.9 Overall SSPB Operation

The overall ISS SSPB operation involves the following main elements:

- Input Power Interface ➔800 W< Columbus Bartolomeo, 3 to 6kW, JEM Exposed Facility Port
- Secondary Conversion: DC Power to Microwave/Optical (~95% efficient depending on voltage multiplier ratio)
- Transmit Aperture: Beam Forming Antenna/Optical Collimator (70%-97% efficient, circa 1992)
- Transmission/Distribution/Control: Free Space Transmission (5%-95% efficient, circa 1992)
- Receive Aperture: Beam Receiving Rectenna/Optical Collector
- Tertiary Conversion: Microwave/Optical to DC Power (~95% efficient depending on voltage multiplier ratio)
- Output Power ➔TBD to Spacecraft Power System Bus Estimated end-to-end efficiency DC input power to DC output power to bus will be greater than 54%.

This will demonstrate SSPB by powering the CubeSat from the ISS-based, frequency-agnostic SDR transceiver, operating between the high end of the Ka band, through W band, and up to eyesafe optical as appropriate.

While use of one or more of the available Ka band (27 to 40 GHz) communications transmitters on ISS may be technically feasible, operations considerations associated with additional use of already burdened ISS mission critical systems are another compelling reason to advance to higher frequencies from the start by using the proposed ISS transceiver. Also, achievable power densities at a specified distance between transmitter and receiver are dramatically higher by increasing beam frequency, despite an anticipated fall off in efficiency. Even more striking is the approximately one-order-of-magnitude reduction in rectenna area required for moving from the Ka Band to the W Band.

2.9.1 SSPB Consortium Members

Over 25 companies, 24 consultants, 4 government agencies, 5 non-profit organizations, 6 Universities, and 3 International Space Agencies are either already a part of the XISP-Inc TD^3 mission development consortium or have made a substantive expression of interest in joining. XISP-Inc is actively recruited potential SSPB consortium members that envision themselves as a stakeholder in the development of Space Solar Power and ancillary services beaming capabilities and infrastructure.

2.9.1 CASIS Implementation Partners

XISP-Inc is currently negotiating with Oceaneering, AIRBUS, Northrup Grumman Innovation Systems, Teledyne Brown, and the ISS U.S National Lab non-profit payload broker Center for the Advancement of Science In Space (CASIS) concerning how to best handle implementation partner responsibilities during each phase of the SSPB TD^3 mission.

2.9.2 Facilities and Other Resources

The ability of XISP-Inc to accomplish the SSPB mission is critically dependent on leveraging existing ground and space facilities and other resources to complete applicable preflight work, ground controls, and space operations. More specifically, two forms of testing are required to accomplish the mission objectives:

- Piecewise iterative testing of components (i.e., Satellite subsystems, ISS transmitter & apertures, Payload Rectenna, radiant energy beaming control and safety interlock system, Other Software/Ancillary Utility Related Components).
- Recursive integrated, mixed-mode end-to-end ground testing / verification & validation with increasing levels of fidelity (Form/Fit/Function Models ➔Protoflight ➔Flight Equipment) is required to accomplish the mission objectives.

SSPB Mission Consortium participants have been chosen in part because of the existing resources they can bring to the mission. It is anticipated that most piecewise iterative testing will be accomplished by the vendors supplying each component by leveraging their in-house testing databases, quality control processes, and facilities. Recursive integrated end-to-end ground testing to accomplish Verification & Validation will be accomplished using resources provided by other SSPB Mission Consortium participants. Examples include higher fidelity integrated testing (i.e., satellite bus, interfaced transmitter, apertures, rectenna, controls, and ancillary components) as well as Temperature/Vacuum, EMI/EMC, and GN&C/ACS testing, which require specialized facilities.

2.9.3 Ground-based Studies

Ground based studies will be used to converge the family of design solutions for the ISS transceiver and the CubeSat rectenna. In conjunction with the NASA ARC Mission Control Technologies Laboratory as well as other interested parties, the initial ground testbed work has a numbered of defined objectives:

- Define and implement/prototype a scalable parametric model for unbundled power systems for sustained free-flyer spacecraft operations extensible to infrastructure operations, propulsion, and/or surface operations.
- Exercise the parametric model to demonstrate:
  - An understanding of the unbundled power system trade space,
  - Any interactions between and with unbundled power system elements, both in terms of what is known and what is known to be unknown,
  - Unbundled power system element specifications, as well as
  - A characterization of all required interfaces.
- Inform and facilitate the technology development by supporting mixed mode simulation using a combination of existing equipment analogs, protoflight equipment, and flight hardware. This will allow simulations with increasing fidelity to both validate the parametric model for incorporation into a near real-time state model of the unbundled system and support the verification and validation of all SSPB mission required interfaces.
- Provide a means to infuse the best available transceiver and rectenna technology development enhancements from the SSPB Mission Consortium researchers into the SSPB mission systems engineering process

It is anticipated that as part of the SSPB mission verification & validation work, multiple ground-based walk throughs of the entire mission operations planned sequences, as well as degenerate failure cases, will be accomplished. Both the ground and flight experiments will make use of the XISP-Inc MOCA (Mission Control and Operations Application) - a web-based application of the XISP Xlink near–real-time state model extended NASA ARC Mission Control Technologies OpenMCT software suite) and an IPv6 Delay/Disruption Tolerant Networking (DTN)-enabled implementation of WAVElan SECurity using IPsec (WAVESEC) compatible with the Immortal Data Inc. Shipslog Data Capture and Analysis system. Unless the WAVESEC link is established, authorized, and validated, outbound transmitter power will be inhibited to a minimum sensible level.

The Alpha Cube Sat Preliminary Design (which serves as the baseline for the SSPB 6U flight test article) Flight Readiness Review assessed all required flight elements as well as their constituent systems/subsystems and has found them to be within the stated TRL bounds of the mission.

2.10 Programmatics

In addition, to the technical considerations the Programmatics associated with orchestration of a TD^3 mission of this scale are substantial for a small business concern and yet it also requires a level of organizational nimbleness seldom exhibited with larger companies. This section addresses many of these aspects.

2.10.1 Feasibility of Project Success- Financial

XISP-Inc will transition from what is de facto a startup company and grow from one employee to approximately 5 employees (technical + administrative), plus consultants and consortium participants to support Phase I of this mission, and will be poised to continue growing as mission execution moves forward and the ground work for creating the first space-based Electrical Power and Ancillary Services Utility is laid. The planned investment tranches are:

- Phase 1 technology development will leverage the IRaD work and other assets of the SSPB consortium participants resulting in products that are useful for the SSPB mission and other space and terrestrial applications. Hence the initial customers are the SSPB consortium. It is anticipated that the combination of secondary market volume which reduces the unit costs of required SSPB elements as well as newly developed power beaming and ancillary services intellectual property will result in a positive balance sheet for XISP-Inc as well as make the Phase II Technology Demonstration a compelling investment for an evolving set of SSPB consortium participants as well as allow for XISP-Inc debt/equity financing.
- Phase II technology demonstration has two defined alternatives.
  - Alternative A assumes minimum Cygnus integration, the SSPB flight package will be a Cygnus secondary payload flown at a concessionary rate with the product being a proven ability to deliver power and ancillary services to the respective Cygnus core payload interfaces. If this alternative is taken it is anticipated that the XISP-Inc balance sheet will continue to improve in this Phase but XISP-Inc

will have to continue to rely on a combination of secondary market volume and investment from an evolving set of SSPB consortium participants as well as XISP-Inc debt/equity financing to cover operational costs in this Phase. It is anticipated that the results of the Phase II mission will allow a compelling case to be made for the Phase III Technology Deployment investment by an evolving set of SSPB consortium participants as well as well as XISP-Inc debt/equity financing.

  - Alternative B assumes full Cygnus integration, the SSPB flight package will be Cygnus infrastructure which delivers power and ancillary services to respective Cygnus core payload interfaces. The resources provided would be paid for and used by the other Cygnus secondary payloads for which an ISS crew-tended co-orbiting lab with more stringent micro-gravity specifications and more flexible experiment protocols, and with product return capability would be of value. If this alternative is taken it is anticipated that the XISP-Inc balance sheet will continue to improve in this Phase and net income sufficient to cover the Phase I and Phase II financing with some profit will be achieved. It is anticipated that the results of the Phase II mission will allow a compelling case to be made for the Phase III Technology Deployment investment by an evolving set of SSPB consortium participants as well as well as XISP-Inc debt/equity financing.

- Phase III technology deployment assumes the value of the resources provided for and used by the other Cygnus secondary payloads for which an ISS crew-tended co-orbiting lab with more stringent micro-gravity specifications and more flexible experiment protocols, and with product return capability would cover the cost of the required equipment, operations, and allow for a compelling profit. This could be achieved by XISP-Inc leasing the Cygnus module after ISS delivery for some number of cycles from Northrup Grumman Innovative Systems (NGIS) and selling the payload space, or an innovative brokerage arrangement with NGIS achieving the same. It is anticipated that the results of the Phase III mission will allow a compelling case to be made for follow-on technology development, demonstration, and deployment work driven by investment by an evolving set of SSPB consortium participants as well as well as substantial infrastructure debt/equity financing consistent with terrestrial power generation and transmission capacity building including the provision of ancillary services.

- Follow-on work is the evolution into an electrical power and ancillary services utility for Cislunar space, the Lunar Power & Light Company™ (LP&L) offering a range of value-added Space and Earth services.

Profits from the work on the SSPB mission will be leveraged to develop other missions in the XISP-Inc commercial mission set. To date, there is no market per se for electrical power utilities in space; every spacecraft has to bring their own. For current spacecraft, except for the ISS, there is no recovery capability from infant mortality, degradation, or unanticipated failures. With the advent of satellite servicing capabilities in the years to come, some additional options will become available. The ability to support a progression of electrical power utility delivery ranging from Emergency ➔ Servicing ➔ Augment ➔ Backup ➔ Primary is projected to lead to incremental revenue growth.

As space development activities expand, driven by new market opportunities and lowering launch costs, the addressable markets for power will become more tractable. It is anticipated that the opening of each addressable market will result in a strong step function of growth in the space electrical utility market. As noted previously, the largest customers for power in Cislunar space are the Geosynchronous Communications Satellites (~443 active), with electrical energy demands ranging from ~2 to ~20 kW. The satellite communication market is splitting into two: a new market for large constellations of small satellites to serve some combination of acceptance-level customers (Quality of Service [QoS] provided is what can be delivered) and special purpose customers that will now be able to afford dedicated satellite communications, and a maturing QoS-driven market commodity market. The latter is evolving to larger and increasingly immortal platforms with plug-in/plug-out technology and rapidly increasing electrical energy demands. The ability to provide power and ancillary services to address both of these markets as a progression from Emergency ➔ Servicing ➔ Augment ➔ Backup ➔ Primary will increase in value over time, and will prove to be mission enhancing if not mission enabling as new systems are designed to use the evolving capabilities.

The early implementation of a power beaming demonstration on the ISS coordinated by XISP-Inc could enhance and enable the demonstration of other power beaming designs and hasten the implementation of commercial space station augments and extensions to service this and other Cislunar markets.

The situation with respect to ancillary services has some available utilities but they tend to be limited, fragmented, and not designed for interoperability. The inclusion of ancillary services utilities will broaden and accelerate market growth.

The socioeconomic benefit of this work includes reinforcing the United States leadership in the global high-tech marketplace, as well as providing opportunities for international cooperation and collaboration. In practical terms, the success of the SSPB mission will impact the trade space for meeting the electrical power and ancillary service requirements for a variety of emerging addressable Cislunar markets, starting with the ISS LEO co-orbiting market and proceeding to other markets as operational systems can be fielded. Numerous entities, including government (e.g., NASA, DoD, and DHS) and commercial (e.g., Northrop Grumman Innovation Systems (formerly OrbitalATK), ViaSat, United Launch Alliance, Made In Space, Blue Origin, OrbitFab), have expressed interest in being customers for beamed power and/or ancillary services. XISP-Inc is part of the ULA-sponsored Cislunar Marketplace development effort involving over 150 entities, and intends to evolve to serve the anticipated $3 to $8 billion/year market for Geo Comsat power within 10 years and other addressable markets from the Karman Line (100 km) up through to the surface of the Moon.

2.10.2 Impact of Innovation

The shift from mandatory self‐sufficiency for the lifecycle of a spacecraft to the availability of an evolving set of utilities and servicing options is a fundamental and inevitable economic/design paradigm shift that the SSPB mission is designed to exploit. The core innovation/advancement is that power and ancillary services beaming allows for the more parsimonious use of resources and ephemeralization "the doing of more with less," as well as the determination as to whether there are economies of scale to be found with power generation and distribution in space. The results of this mission will not only be enhancing for other missions, they will be enabling. This will allow for a wider range of opportunities for further space exploration and development to come to fruition. XISP‐Inc not only plans on publishing the results of the SSPB mission, but the generation of papers, presentations, and follow‐on proposals are an integral part of the mission. The results of the mission are the most effective marketing for commercial follow through. The results will entail a well‐curated characterization of what is public domain, what is owned intellectual property, and how licenses can be readily obtained supported by agreement of the SSPB Mission Consortium. The SSPB mission development work to date has already established the proposed principal investigator as a leading researcher in the field of space solar power/radiant energy beaming application development.

2.10.3 Benefit to Humankind and Social Impact

The SSPB mission will engage multiple generations of engineers to develop new capabilities, infrastructure, and human capital that will help prepare our nation and world for the challenges of the 21st century and beyond. The near-term benefit of this mission is that it increases the available resources of the ISS National Lab by facilitating and supporting the operation of crew-tended co-orbiting free-flying systems. In the mid-term, the Cislunar electrical and allied utilities services will prove valuable in supporting the growing utility needs of the next generation of Earth- and space-facing applications, satellites, platforms, and facilities. In the long term, Space Solar Power technology may prove instrumental in meeting both the United States' and the world's baseload electrical energy demand in a cost-effective, safe, and environmentally benign manner, as well as saving lives by rapidly delivering power to disaster areas and other mission-critical environments.

The SSPB mission has benefited from an extended mission development process that has included years of peer review at multiple levels and vetting by government (NASA, DoD, NOAA, DHS, etc.) and commercial interests (Raytheon, Northrop Grumman, Made In Space, ULA, etc.). The proposed work is deemed as applied engineering, not new physics. Accordingly, the preponderance of evidence suggests that it is not only feasible but a tractable mission that results in practical applications to other missions. The practicality and efficiency of the end‐to‐end systems deployed from this effort will drive their subsequent inclusion in future infrastructure/spacecraft designs.

2.10.4 Feasibility of Project Success - Orchestration

XISP-Inc has already provided substantial cash and In-kind funding (in excess of $1 million), and all SSPB Mission Consortium members have agreed to contribute at least a minimum Industry Contribution of 25% (cash and In-kind). Multiple members of the SSPB Mission Consortium are capable of contributing a meaningful amount of SSPB project funding and Intellectual Property, and all compensated consortium members will meet or exceed the minimum industry contribution required. Furthermore, assuming success of the project, multiple members of the SSPB Mission Consortium have the resources and are committed in principle to help commercialize the results. It is anticipated that given an allocation of the ISS National Lab resources, commercial cargo space, integration verification & validation support, and a modest amount of mission development funding, XISP-Inc will be able to raise the remaining funds required through a combination of grant, debt, and/or equity financing. XISP-Inc has received a written acknowledgment from AA for HEOMD that NASA is willing to consider direct funding to add additional milestones and/or accelerate milestones if conditions are met.

The research methodology and operational approach has been developed on an iterative and recursive basis through over 5 years of technical peer review of presentations, papers, and proposals in close cooperation/collaboration with internationally recognized experts in the field, including the proposed Principal Investigator. NASA HEOMD has stated through proposal evaluation that the proposed team has the necessary and appropriate experience and expertise. The research plan is robust enough to sustain the interest and desire to participate in the SSPB Mission Consortium. The flight hardware options have been vetted through multiple means and processes. In addition, provisions have been made to ensure that the mission has a baseline path for successful execution and sufficient optional overlays (e.g., multiple technologies, multiple vendors, scalable tests, balanced interests/objectives/agendas) to mitigate all cost, schedule, and technical risks identified to date. The required hardware and software leverages existing COTS products and past and current IR&D work.

In Phase 2, the Northrop Grumman commitment to a Cygnus demonstration becomes the first customer served, accommodating their requirements for fault-tolerant power and ancillary services for both co-orbiting free-flying spacecraft and payload operations. The key business driver is that there are economies of scale to be found in the generation and transmission of power and ancillary services in space for customer applications. We anticipate that the SSPB TD^3 mission will lay the technological foundation for our Cislunar electrical power and ancillary services entity, the Lunar Power & Light Company™ (LP&L). LP&L intends to serve the anticipated $3 to $8 billion/year market for Geo Comsat power within 10 years and other addressable markets from the Karman Line (100 km) up through to the surface of the Moon. XISP-Inc is part of the ULA-sponsored Cislunar Marketplace development effort, which involves over 150 entities. It is anticipated that the combination of the revenue from the power and ancillary services provided to the ISS co-orbiting/LEO customers and the value of the perceived and/or real cost, schedule, and technical risks retired by the TD^3 mission will realize a large-enough return to secure the follow-on investment required to build out the Lunar Power & Light Company™.

XISP-Inc received input from NASA JSC Code OZ regarding our January 20, 2017 submittal on the RESEARCH OPPORTUNITIES FOR ISS UTILIZATION NASA Research Announcement: NNJ13ZBG001N Soliciting Proposals for Exploration Technology Demonstration and National Lab Utilization Enhancements. This input stated as follows: "NASA has determined that Space-to-space power beaming is of interest to NASA and has the potential to affect a wide range of missions and is a potential key element of space infrastructure for the future. Overall, the proposal [proposed mission] is relevant to NASA's exploration goals and reflects the involvement of a team with appropriate experience." The Department of Defense (DoD), National Oceanic and Atmospheric Administration (NOAA), and Department of Homeland Security (DHS) all operate (or would like to operate) satellite systems capable of using power and ancillary services beaming to meet specific requirements for performance, availability, and security.

There is an open market for degrading legacy systems in the near term, an evolving market for new enhanced satellites in the mid-term (~2 to ~5 years), and an essential element of "immortal" serviced platform systems that will be designed to accommodate multiple generations of payloads in the long term (~5 to ~10 years). Any enhanced electrical power and ancillary services made available on an in situ and/or beamed basis to customers will be reflected directly as an increased ROI even after accounting for the recurring costs. Any electrical power and allied utility services made available would prove to be mission enhancing if not mission enabling, and has the potential for creating a reoccurring revenue stream.

XISP-Inc anticipates a market for ancillary services (i.e., communications, data, and navigation/time) and strategies for achieving an Interoperable Network Communication Architecture (INCA) as well as the Quality of Service (QoS) requirements (i.e., performance, availability, and security). Frequency-agnostic, (e.g., Software Defined Radios, electro/optical converged electronics, and selectable apertures) pervasively networked communications and data systems with provisions for Delay and Disturbance Tolerant Networking (DTN), including store and forward capacity, and QoS-based routing will likely be essential.

While the immediate environmental impact of the SSPB mission will be negligible aside from some additional operational rules, the value proposition of Space Solar Power technology for Earth-facing applications, on-orbit operations, and space-facing applications holds great promise. More specifically, applications of power beaming technology for orbital debris mitigation and for the potential for large-scale energy transfer are two areas that could have a dramatically positive environmental impact.

2.10.5 STEM and Educational Outreach

XISP-Inc intends to provide opportunities for constructive engagement of undergraduate and graduate students in academic-schedule–compatible capacity-building research and operations work directly supporting space TD^3 missions. Opportunities are being crafted with a variety of universities to support the integration of enhanced flight test article components and innovative testbed research tracks, as well as experiment operations via virtualized operations centers. In addition, as a rapidly advancing TD^3 mission, there are multiple opportunities for aspirational and technical STEM teaching moments based on the technical details of the mission as well as the potential applications that can be tailored to K-12 students. XISP-Inc maintains involvement with multiple STEM outreach and engagement activities involving non-profit and university partners including, but not limited to, University of Maryland Space Systems Lab Design Review Participation.

XISP-Inc appreciates the importance of public information generation and dissemination at all levels, including both a vigorous peer review and STEM education component, as an integral part of the proposed mission. XISP-Inc has developed and maintains relationships with a wide range of space advocacy organizations including the National Space Society & affiliated organizations, Students for the Exploration and Development of Space (SEDS), and the Space Foundation.

XISP-Inc will implement a state-of-the-art Colab website for the SSPB mission, which will enable virtual cooperation, collaboration, and workflow between participants located around the country including the wider STEM community. XISP-Inc will maintain a public website section of this site providing an ongoing summary of the SSPB mission status and all publicly released SSPB mission work products.

3. Theory and calculation

Previous papers by the authors have modelled predicted performance both in terms of theoretical power density achievable at a given distance, input power, transmit aperture area, rectenna aperture area, for a specified frequency as well as the power received for a defined power density and rectenna aperture area. The predicted performance was found to correlate well with other investigator's models that have been benefited from actual ground test and the XISP-Inc model has been refined in cooperation with those investigators. The latest estimated deliverable power-density and power-received values based on the collection efficiency calculations (which have been correlated to ground tests by other researchers) provide a compelling comparison between estimated delivered power density and the Solar Constant for the orbital distance of immediate interest. The calculated values clearly show that the low end of the Ka band (i.e., 26.5 GHz shown), with a delivered power density an order of magnitude less than the Solar Constant, is very benign. The high end of the Ka band (i.e., 36 GHz shown) can actually meet some customer requirements, though at best at a small multiple of the Solar Constant. However, the W band (i.e., 95 GHz) can provide a power density an order of magnitude or higher than the Solar Constant. The challenge in all instances is engineering systems with an end-to-end efficiency which is satisfactory and sufficient for the application. Space solar power technology holds the promise of being one of the few large-scale energy generation options that can scale to meet the growing electrical energy demand in space. This mission is a unique opportunity to foster the development of SSPB by leveraging ground based piecewise testing and ISS resources to create an integrated SSPB testbed environment on and near the ISS that supports the development of frequency-agnostic-radiant-energy beaming technology.

4. Budget and Schedule

The total estimated time to complete the SSPB TD^3 mission as scoped for all three defined Phases is thirty-six (36) months. The runout budget estimate (both cash and In-kind contributions) for the SSPB TD^3 mission is less than $13 million. The budget estimate for just Phase I is less than $7 million. The total funds are to be raised and contributed by members of the Consortium. Current key commercial members of the consortium include: XISP-Inc, Raytheon, Northrup Grumman Innovation Systems, Made In Space, Satellite Bus & System Vendors (bid out), Immortal Data, Deep Space Industries, AIRBUS, Oceaneering, and Tethers Unlimited. XISP-Inc requires the SSPB mission to have recognizable standing (i.e., CASIS approval) in order to complete the commercial capital raise required to execute the SSPB mission. The balance of required funds will have to be raised from a combination of grants, NASA Space Act Agreement funded milestone achievement contracts, Department of Defense CRADA contracts, equity financing, and debt financing.

The total CASIS Implementation Partner preliminary budget assumes Implementation Partner assistance with one (1) 6U CubeSat flight test article installed in a mission-appropriate deployment canister. The flight test article shall use H_2O-based thrusters. The flight test article shall be shipped to station as soft pack pressurized cargo on a commercial cargo flight and one (1) Columbus Bartolomeo exposed facility and JEM Exposed Facility compatible payload carrier (less than 450 kg) shipped to the station as unpressurized cargo on a commercial cargo flight. The CASIS Implementation Partner will be an integral part of the Mission Development and Technology Development Phases of the SSPB mission. The Implementation Partner costs associated with same are XISP-Inc estimates based on conversations with multiple vendors. It anticipated that the majority of the Implementation Partner Northrop Grumman Innovation Systems Cygnus costs will be In-kind.

The top level milestone schedule is shown in Table 3 -- SSPB Phase I, II, and III Milestone Schedule. The mission budget assumes a minimum level of NASA direct funding each year as a placeholder for potential direct participation by NASA by either adding additional milestones and/or accelerating milestones along with the commensurate funding for accomplishing the same. In the broader context the SSPB TD^3 mission maps well into a phased effort to develop Space Solar Power technology as shown in Figure 6 – Energy TD^3 Milestones.

5. Conclusions

Achieving the promise of moving to W band (i.e., 95 GHz) and even higher frequencies, including eye safe optical which can provide beam power densities an order of magnitude or higher than the Solar Constant shows promise for enhancing if not enabling new missions in Cislunar space and beyond. The challenge in all instances is engineering systems with an end-to-end efficiency which is satisfactory and sufficient for the application. The ability to provide power when and where needed is essential to virtually all aspects of human endeavour, and is enabling for any form of space development/settlement. Space solar power technology holds the promise of being one of the few large-scale energy generation options that can scale to meet the growing electrical energy demand in space. This mission is a unique opportunity to foster the development of SSPB by leveraging ground based piecewise testing and ISS resources to create an integrated SSPB testbed environment on and near the ISS that supports the development of frequency-agnostic-radiant-energy beaming technology.

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Table 1. Comparing Beaming Power Density and the Solar Constant

	Power Density (Watts/cm^2)	Power Density (Watts/cm^2)	Power Density (Watts/cm^2)
	P_d	**P_d**	**P_d**
	Case 1 @26.5 GHz	**Case 2 @36 GHz**	**Case 3 @95 GHz**
Case 1. Power Density with D=200 m, Pt= 3000 W and At = 1642 cm2	0.00964	0.01774	0.12331
Case 2. Power Density with D=200 m, Pt= 6000 W and At = 1642 cm2	0.01929	0.03549	0.24661
Case 3. Power Density with D=200 m, Pt= 3000 W and At = 10000 cm2	0.05874	0.10809	0.75108
Case 4. Power Density with D=200 m, Pt= 6000 W and At = 10000 cm2	0.11747	0.21617	1.50216
I_{sc} = *Solar Constant at 1 AU = 0.1367 Watts/cm2*	P_d significantly lower than I_{sc}		
	P_d similar to I_{sc}		
	P_d significantly higher than I_{sc}		

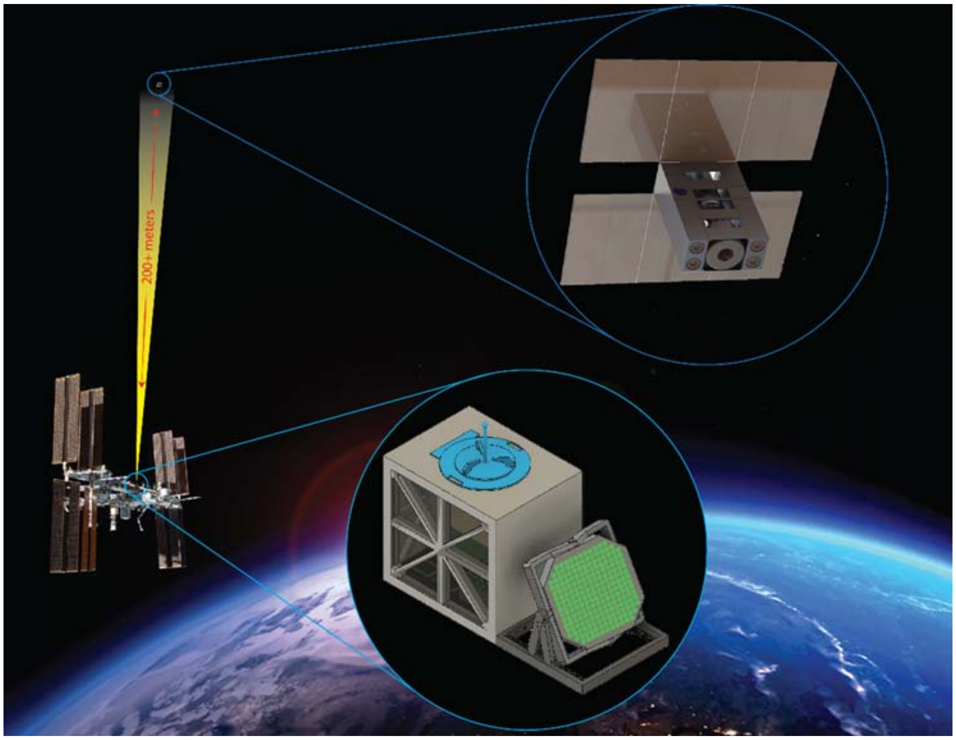


Fig. 1. SSPB Overview

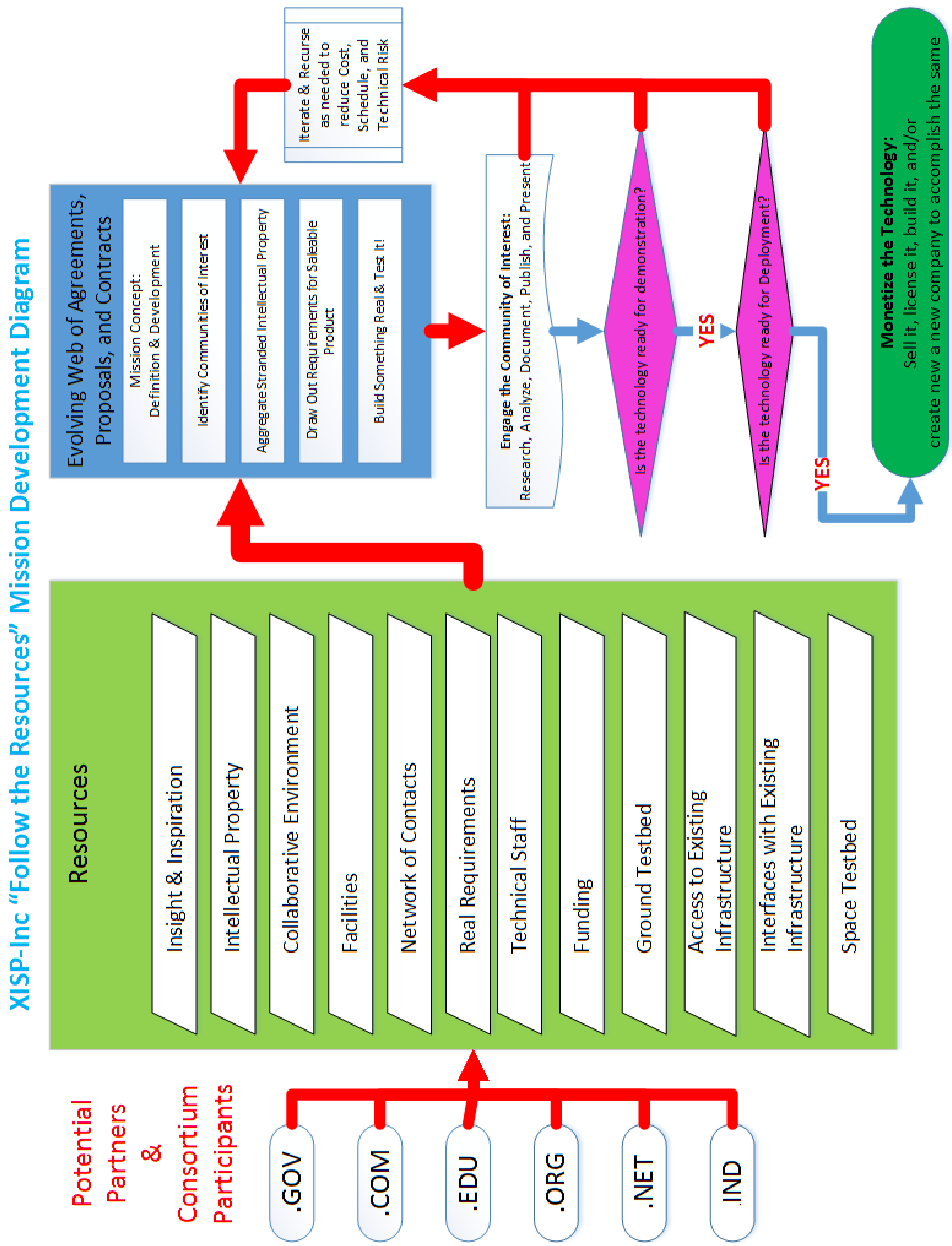
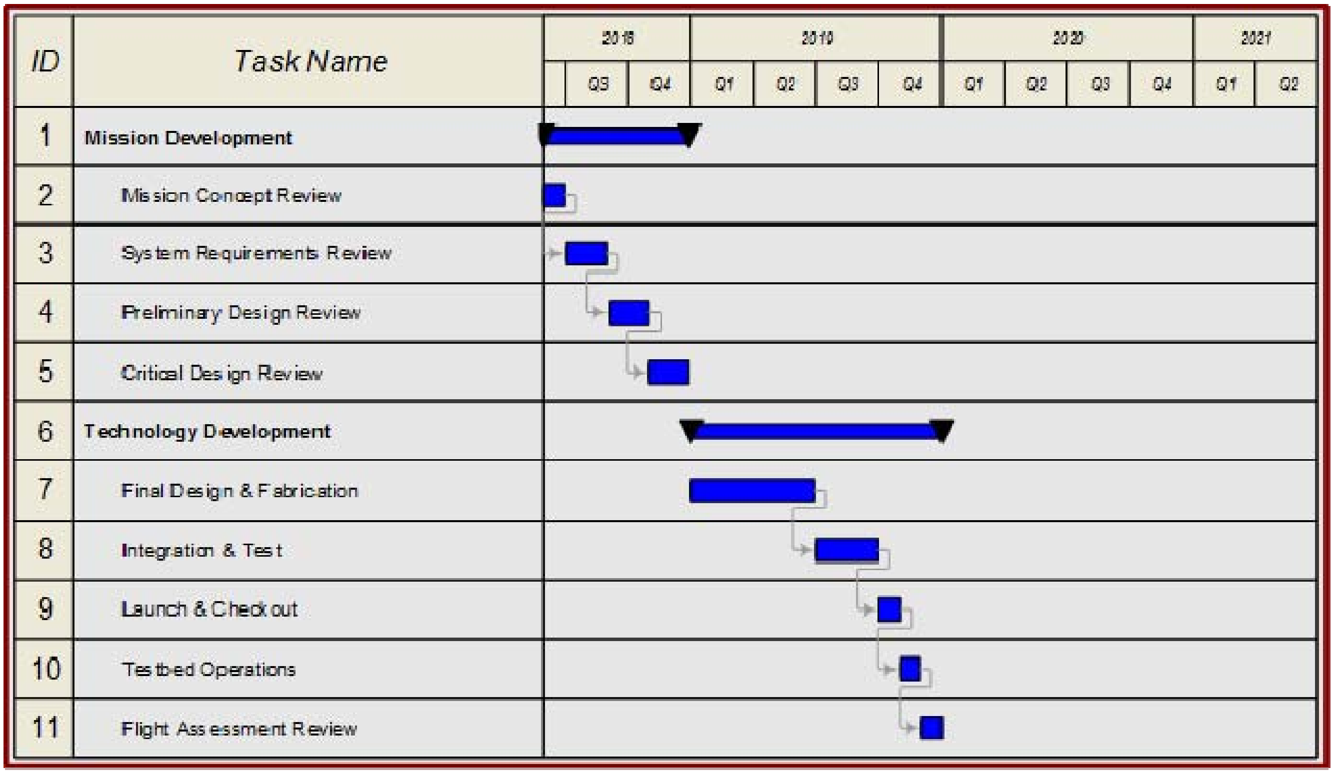


Figure 2 – Follow the Resources Mission Development Process

Table 2 - 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
ISS co-orbiting crew-tended free-flying laboratory / manufacturing space	• Not available. Fault- tolerant utilities and an evolved concept of operations are required.	• Repurposes pressurized logistics carriers at low cost • Can provide additional level of utility failure tolerance • Can provide power augmentation needed for experiments
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 penetrate dust, increasing system end-to-end power collection efficiency • Reduced mass and volume of deployed rovers/surface equipment • "Wipers" are ineffective against strong dust chemical / physical adhesion; elimination increases reliability and reduces 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 is significantly smaller than solar arrays due to higher received power density and greater conversion efficiency, resulting in lower mass and volume of each element and decreased atmospheric drag in LEO • Lower cost to upgrade the elements with new and/or different sensor and communications capability because the power generation system does not need to be replaced • No sun-shadowing constraints, so that system and logistic complexity are reduced • Large numbers of small elements in a disaggregated system provide increased reliability and resilience relative to smaller numbers of larger elements
Sensor platforms with demanding spacecraft dynamics or thermal / structural loads	• Solar arrays • Attitude control systems with sufficient control authority • Thermal stand-offs	• Receiving rectenna significantly smaller, with greater conversion efficiency (reduced mass, volume, inertia, stiffness, and thermal load) than sensor platform solar arrays • Smaller sensor platform attitude control actuators (reduced mass, volume, power requirements) • Simplified thermal and structural design of the sensor platform • Orbit can be optimized to sensor requirements by removing constraint of solar array pointing
Large power consumers in Earth Orbit (e.g., ComSats)	• Carry large PV arrays, currently less than 40kW	• Moving power generation on the ComSat balance sheet from CapEx to OpEx • On the Power Utility balance sheet, amortize investment over the life of many satellites, and many generations of satellites • Decouple ComSat earth-pointing and station-keeping requirements from power generation sun-pointing and eclipse avoidance requirements • Economies of scale in the power generation equipment, as one power generation satellite can service perhaps 100 ComSats

Table 3 – SSPB Phase I, II, and III Milestone Schedule



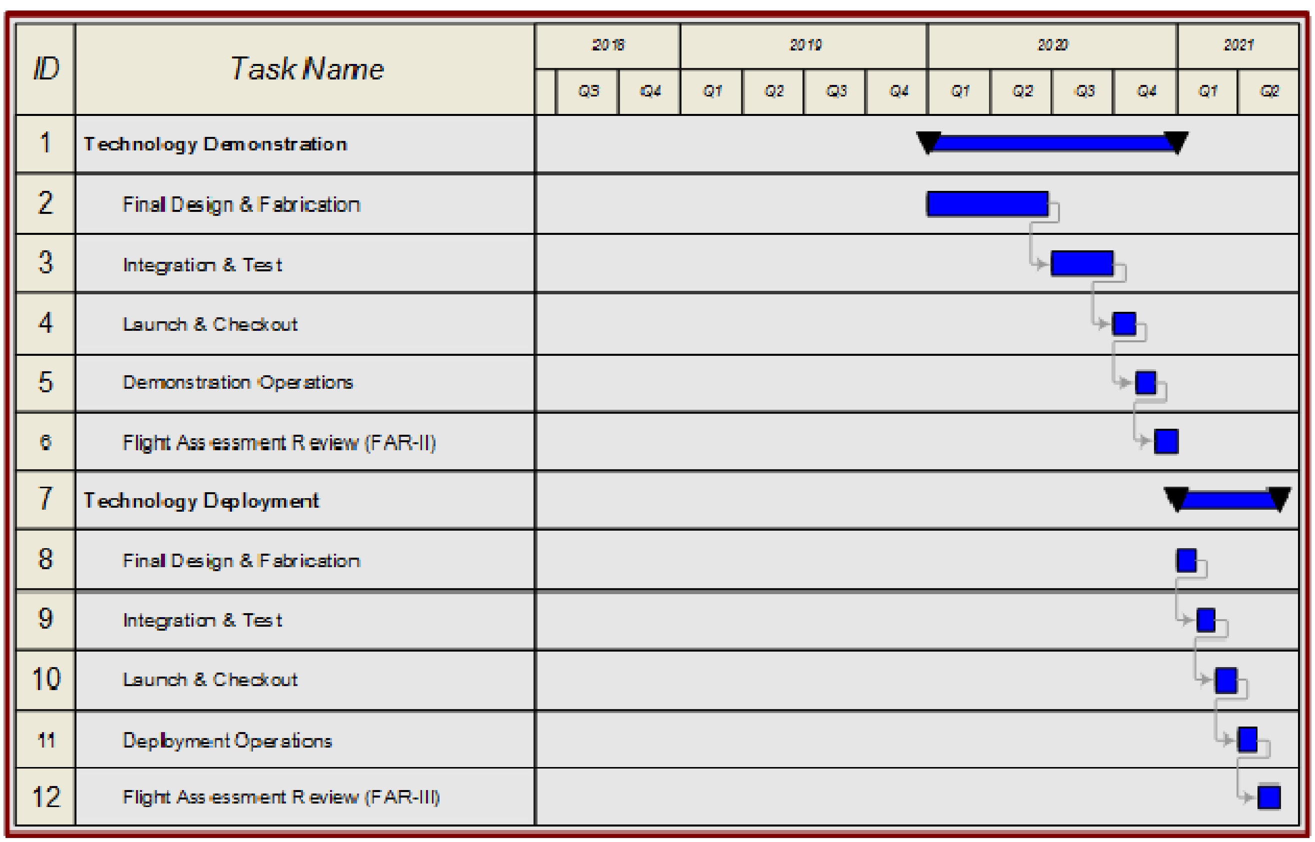


Figure 3 – Space-to-Space Power Beaming Concept of Operations

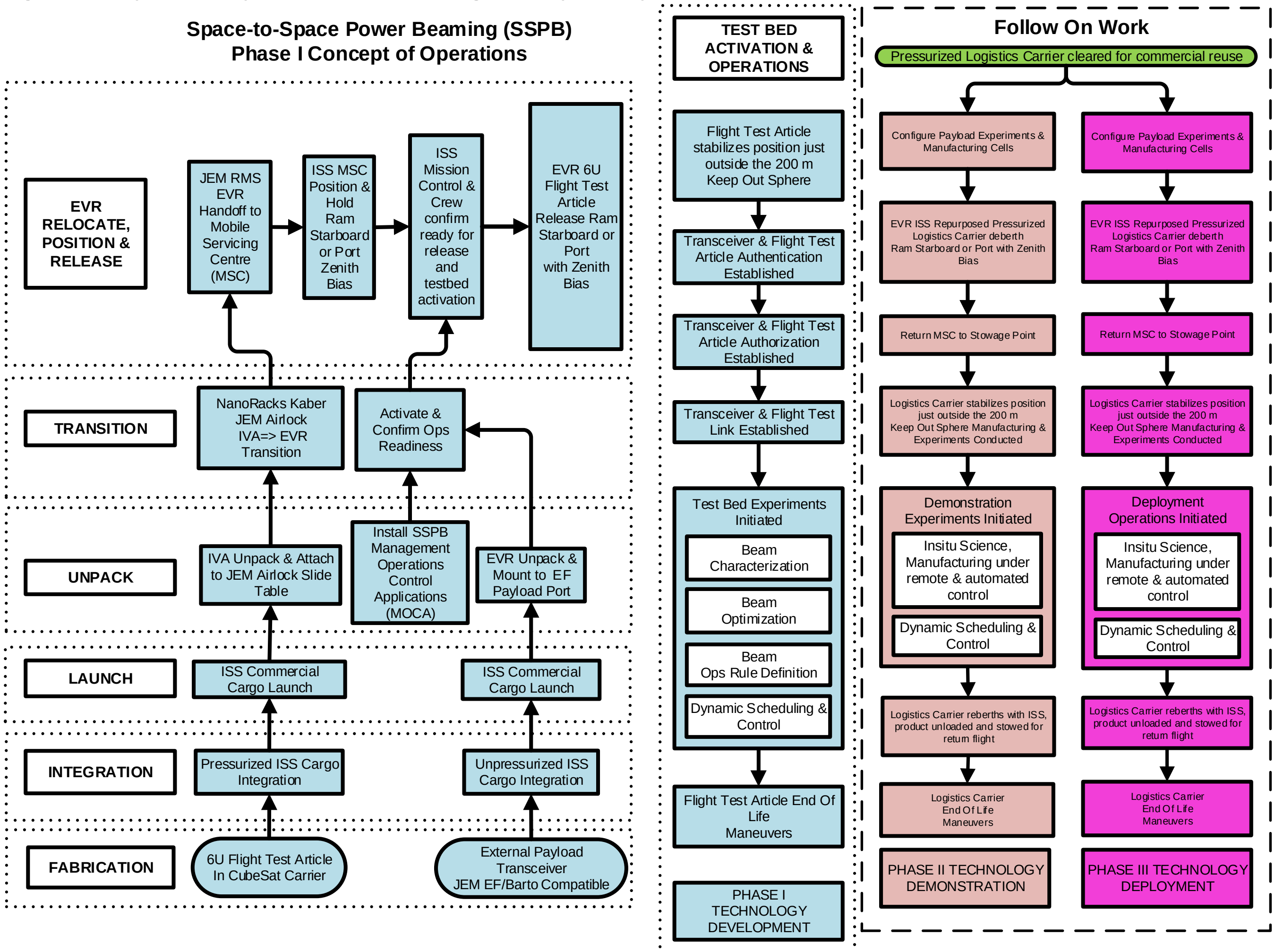


Figure 4 – SSPB ISS Transceiver Payload

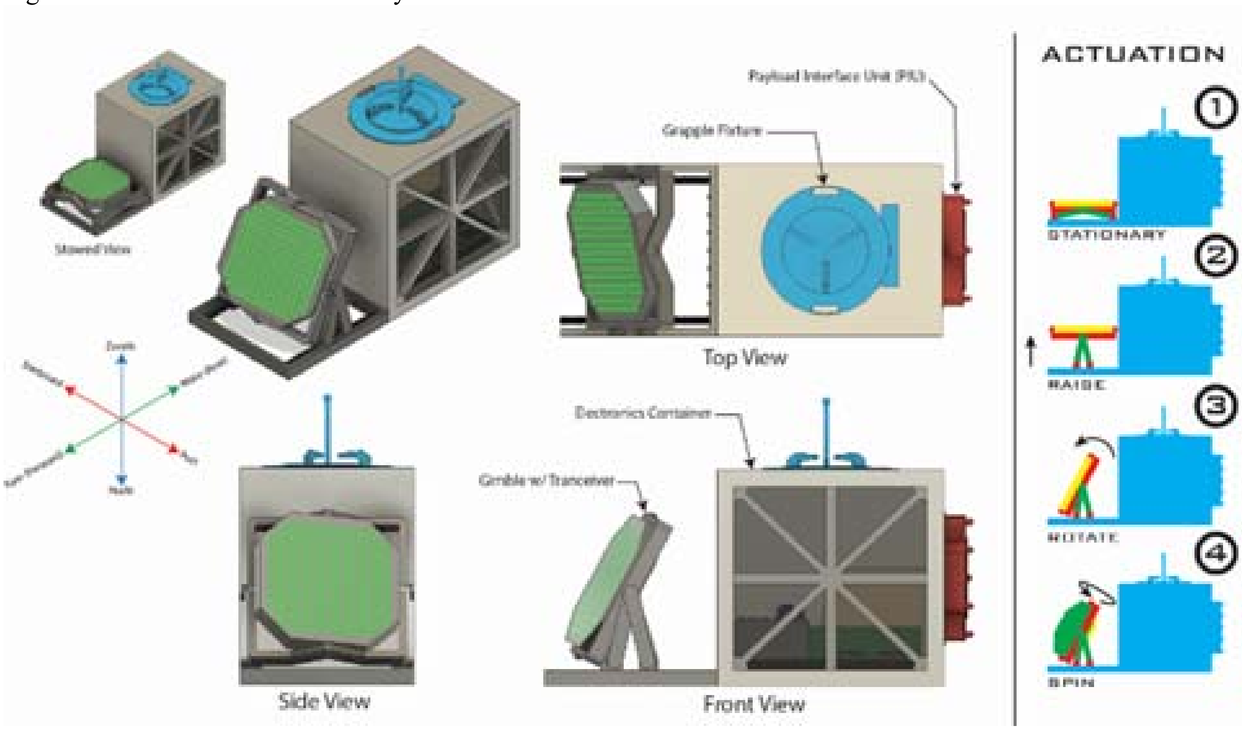


Figure 5 – XISP Satellite Bus will be of similar design to 6U Alpha Cube Sat on the right side of the figure. Layered reflectarray technology on left will replace the solar panels.

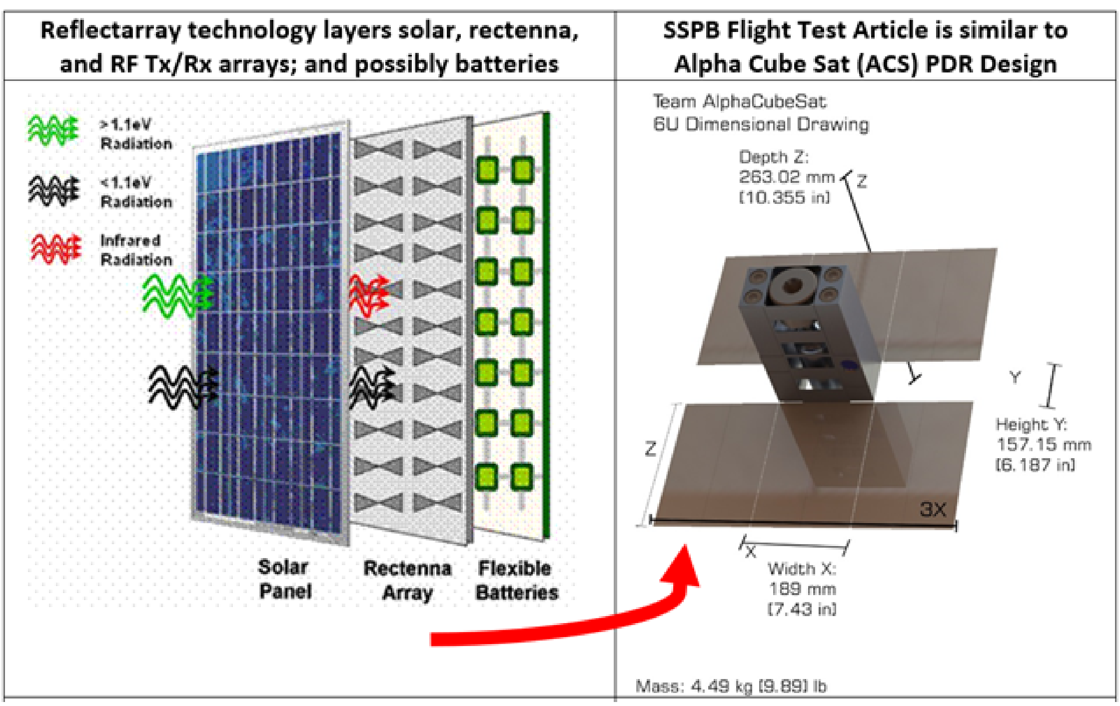


Table 4 – SSPB Payload Accommodation Requirements

XISP-Inc SSPB Payload Specifications v1.1			
	ISS Transceiver	6U Flight Test Article	Cygnus
Payload Accommodation Type	Bartolomeo: Double Payload (Barto); Standard EF Payload (JEM EF)	Not Applicable	Not Applicable
Launch Type	Unpressurized Cargo	Pressurized or Unpressurized Cargo	Pressurized Logistics Carrier
Field of View	Ram and Zenith, gimballed phased array aperture	Station facing with active attitude control system from Ram, Starboard/Port, with Zenith Bias co-orbit > 200 m from ISS center of mass (NASA recommended location for maximum safe dwell time with active attitude control and Min Required distance based on ISS Keep Out Sphere)	Station facing with active attitude control system from Ram, Starboard/Port, with Zenith Bias co-orbit 1 to 10 km from ISS center of mass (NASA recommended location for maximum safe dwell time with active attitude control and Min Required distance based on ISS Keep Out Sphere)
Geometric Envelope Dispenser	Not Applicable	Planetary Systems Canisterized Satellite Dispenser (CSD) 402.1 x 263.53 x 157.66 mm (CSD Spec)	402.1 x 263.53 x 157.66 mm (equivalent to CSD Spec)
Geometric Envelope Payload	1000 x 800 x 1600 mm	365.9 x 239.4 x 109.7 mm (CSD Spec)	365.9 x 239.4 x 109.7 mm (equivalent to CSD payload Spec)
Mass of Dispenser	Not Applicable	4.50 kg +/- 3% (CSD Spec)	4.50 kg +/- 3% (CSD Spec)
Mass of Payload	450 kg max (Barto); 500kg max (JEM EF)	14.0 kg max (NASA Cube Quest Challenge limit)	~14.0 kg min (thermal requirement accommodations will increase mass)
Power	120Vdc operational power; less than 800 W max, less than 300 W nominal (Barto) less than 6000/3000 W max, less than 3000/1500 W nominal (JEM EF) ; survival power (All)	100 W received power (nominal heat rejection limit); survival power is provided by on-board solar arrays and batteries	Less than 3000/1500 W received power (Cygnus Payload Power Growth/Payload Power Nominal); survival power is provided by on-board solar arrays and batteries
Data Rate	**Hardwire:** Access to gigabit ethernet to SSPB Storage Area Network device on ISS Payload Network throttled as necessary, TBD Mbps max operations, TBD Mbps nominal operations, TBD kbps keep alive, TBD Mbps Downlink/Uplink nominal operations (Barto); Access to gigabit ethernet to SSPB Storage Area Network device on ISS Payload Network throttled as necessary, TBD Mbps max operations, TBD Mbps nominal operations, TBD kbps keep alive, TBD Mbps Downlink/Uplink nominal operations (JEM EF)	Not Applicable	Not Applicable
	Wireless: Alternative WiFi/LiFi to SSPB Storage Area Network device on ISS Payload Network, TBD Mbps max operations, TBD Mbps nominal operations, TBD kbps keep alive, TBD Mbps Downlink/Uplink nominal operations (Barto); Gigabit ethernet to SSPB Storage Area Network device on ISS Payload Network, TBD Mbps max operations, TBD Mbps nominal operations, TBD kbps keep alive, TBD Mbps Downlink/Uplink nominal operations (JEM EF)	**Wireless:** RF Link to SSPB ISS Transceiver, TBD Mbps max operations, TBD Mbps nominal operations, TBD kbps keep alive, TBD Mbps Downlink/Uplink nominal operations	**Wireless:** RF Link to SSPB ISS Transceiver, TBD Mbps max operations, TBD Mbps nominal operations, TBD kbps keep alive, TBD Mbps Downlink/Uplink nominal operations
Surface Area	less than 1 m^2 for transceiver	less than 1 m^2 for rectenna	less than 1 m^2 for rectenna
Payload return	Yes for one or more EVR compatible Orbital Replaceable Units, but not mandatory	No, unless retreival becomes an available option	No, unless retreival becomes an available option
Interface Compatibility	EVR Compatible: SSRMS, SPDM, JEMRMS, GOLD, Bartolomeo Payload, JEM EF Payload	EVR Compatible: SPDM	EVR Compatible: SSRMS, SPDM, JEMRMS

Figure 6 – Energy TD^3 Milestones