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CHALLENGES OF SPACE POWER AND ANCILLARY SERVICES BEAMING: KEY TO OPENING THE CISLUNAR MARKETPLACE

Abstract

This paper addresses the challenges of space power and ancillary services beaming in the context of opening the Cislunar marketplace. More specifically, it provides updated status on the Technology Development, Demonstration, and Deployment (TD^3) mission development efforts for:

- ISS Space-to-Space Power ancillary services Beaming (SSPB)
- Surface-to-Surface Power ancillary services Beaming (SSPasB) for lunar applications
- Space-to-Alternate Surfaces Moon/Asteroids
- Space-to-Earth, as well as the
- Opportunity to upgrade ISS to better serve as a TD^3 platform.

The technology to enable providing wireless utility services (e.g., power, data, communications, navigation, time, heat, etc.) to multiple Clients/Customers (C/C) across Cislunar space (Karman line to the far side of the Moon) in a cost and resource effective manner is now moving forward. The availability of power and ancillary services (e.g., communications, data, navigation, time, etc.) is essential to most if not all aspects of lunar operations. The unbundling of space electrical power systems (i.e., separation of power generation, transmission, distribution, control, and loads) affords opportunities for redistribution of mass, overall volume, surface area, and complexity which can be mission enhancing/enabling. Increasing the availability of power and data transfer performance while simultaneously reducing the resource burden (mass, power, volume) to achieve the same that must be borne by the C/Cs will be mission enhancing if not mission enabling. The narrative of the Cislunar Marketplace as a cooperative, collaborative, and competitive ecosystem of entities engaged in space development speaks to how we can achieve the ”promise of the future”. This is directly relevant to the IAC Congress Theme of ”Space: The Power of the Past, the Promise of the Future”. Going forward space development will accomplished by a combination of entities including: nation state sponsored space agencies, commercial firms, non-profit organizations, universities, inspired billionaires, and individuals that bring unique talents/resources to the table. The realization of space solar power systems across the Cislunar marketplace will be both mission enhancing and enabling. This multidisciplinary paper focuses on engaging the IAF technical audience in a collaborative discussion of the Challenges of Space Power and Ancillary Services Beaming as a Key to Opening the Cislunar Marketplace and the potential solution space for fostering space development. It is envisioned that these workshops could become an integral part of the ongoing work of the IAF and its constituent members, serving as multi-sector” industry” fora.

I. INTRODUCTION

Establishing the “Nexus” of ideas and capital which will enable the formation of the resources necessary to realize the value of power and ancillary services beaming has been the focus of the mission development efforts.

The availability of power and ancillary services (e.g., communications, data, navigation, time, etc.) is essential to most if not all aspects of Cislunar operations.

The unbundling of space electrical power systems (i.e., separation of power generation, transmission, storage, distribution, control, and loads) affords opportunities for redistribution of mass, overall volume, surface area, and complexity which can be mission enhancing/enabling.

Increasing the availability of power and data transfer performance while simultaneously reducing the resource burden (mass, power, volume) to achieve the same that must be borne by the Clients/Customers will be mission enhancing if not mission enabling.

II. KEY CONSIDERATIONS

Space Power and Ancillary Services infrastructure is an applied engineering problem and an economics problem.

Applied Engineering because the solutions are valued in terms of availability, durability, resilience, and maintainability not as new science and/or engineering

Economics because the solutions are necessarily sustainable utilities that will circumscribe what is possible

Each application and venue has:

- significant systems engineering and economic challenges
- different fundamental figures of merit / value proposition.

Operational capabilities are best realized by leveraging a combination of technology development "Push" and mission requirements "Pull". Each increment of public and/or private investment should lead to an operational capability useful and used by one more other missions.

III. KEY VARIABLES

- **Cost/Economics** (initial cost to first power, LCOE, market viability, anchor customers),
- **Frequency/Wavelength** (microwave to eye•-safe optical),
- **Voltage/Amperage** (input, output, transforms)
- **Distance** (near field, boundary regions, far field),
- **Magnitude** (power level supporting applications, scalability)
- **Duration** (pulsed, scheduled, continuous),
- **Availability** (dispatchable, on demand, scheduled, prioritized, by exception, resilience, interoperability),
- **Security** (misuse, interruption, destruction, safety),
- **Performance** (net transfer, end•-to-end efficiency, piecewise efficiency, steering precision and accuracy, beam shaping, effective operational difference),
- **Logistics** (mass, volume, modularity, durability, maintainability),
- **Environmental** (temperature, radiation, degradation), and
- **Technology Readiness Level [TRL]** (cost, schedule, and technical risk)

IV. HYPOTHESIS

The author has hypothesized that unbundling / disaggregating power systems (i.e. the separation of power generation, transmission, control, storage, distribution, and loads) can:

- reduce spacecraft complexity, mass and/or volume
- allow reallocation of spacecraft mass and/or volume
- alter the cadence of spacecraft mission operations
- reduce or eliminate solar pointing requirements
- impart additional delta-V to spacecraft/debris
  - Indirectly (power augmentation)
  - Directly (momentum transfer)

In addition, other novel approaches including but not limited to optical grounding are emerging in cooperation with other researchers.

V. CHALLENGE MATRIX

A challenge matrix (see Figure 1) was prepared by the author to characterize the Space Solar Power Problem Space and the Solution Space as a means of addressing incremental approaches to the development of space solar power technology. The challenge matrix addresses two primary work vectors:

Technology Readiness Level (TRL) Advancement:
Development ➔ Demonstration ➔ Deployment

Relative Value of Delivered Power by Venue:
Space-to-Space ➔ Surface-to-Surface ➔ Space-to-Alternate Surface ➔ Space-to-Earth

The Challenge Matrix is intended to support the definition of application overlays and draw out the synergistic relationship between work accomplished for different venues.

The challenge with TRL advancement is being able to bridge the technology development valley of death and achieve a deployable system for each increment of resources committed without compromising the ability to further evolve the system. This requires logical bounds for each increment of investment. For example the existing ISS infrastructure can support up to 6 kW of input power to a single payload using two 3 kW Remote Power Controller circuits in certain locations (e,g, the JEM Exposed Facility). Given the current ISS power generation limit of ~100 kW delivered to the power bus for use the input power limit for initial testing is effectively bounded. However, the ISS power system was designed to enable power services up to 300kW delivered to users (i.e., 100 kW via the photovoltaic system and 200 kW from a modular solar dynamic system using eight 25 kW modules). Accordingly, such an augment could enable the ISS to become a major power and ancillary services beaming resource for LEO co-orbiting systems and potential tests supporting systems in other locations.

The challenge with respect to different venues is that all have different fundamental figures of merit that are driven by the relative value of delivered power. For space-to-space applications the value per unit of power is very high since the availability of the same is mission enhancing if not mission enabling, and therefore directly impacts the Return On Investment (ROI) for impacted systems. For other venues the relative economics becomes a significant factor. For Space-to-Earth the economics dominates the relative value calculation.

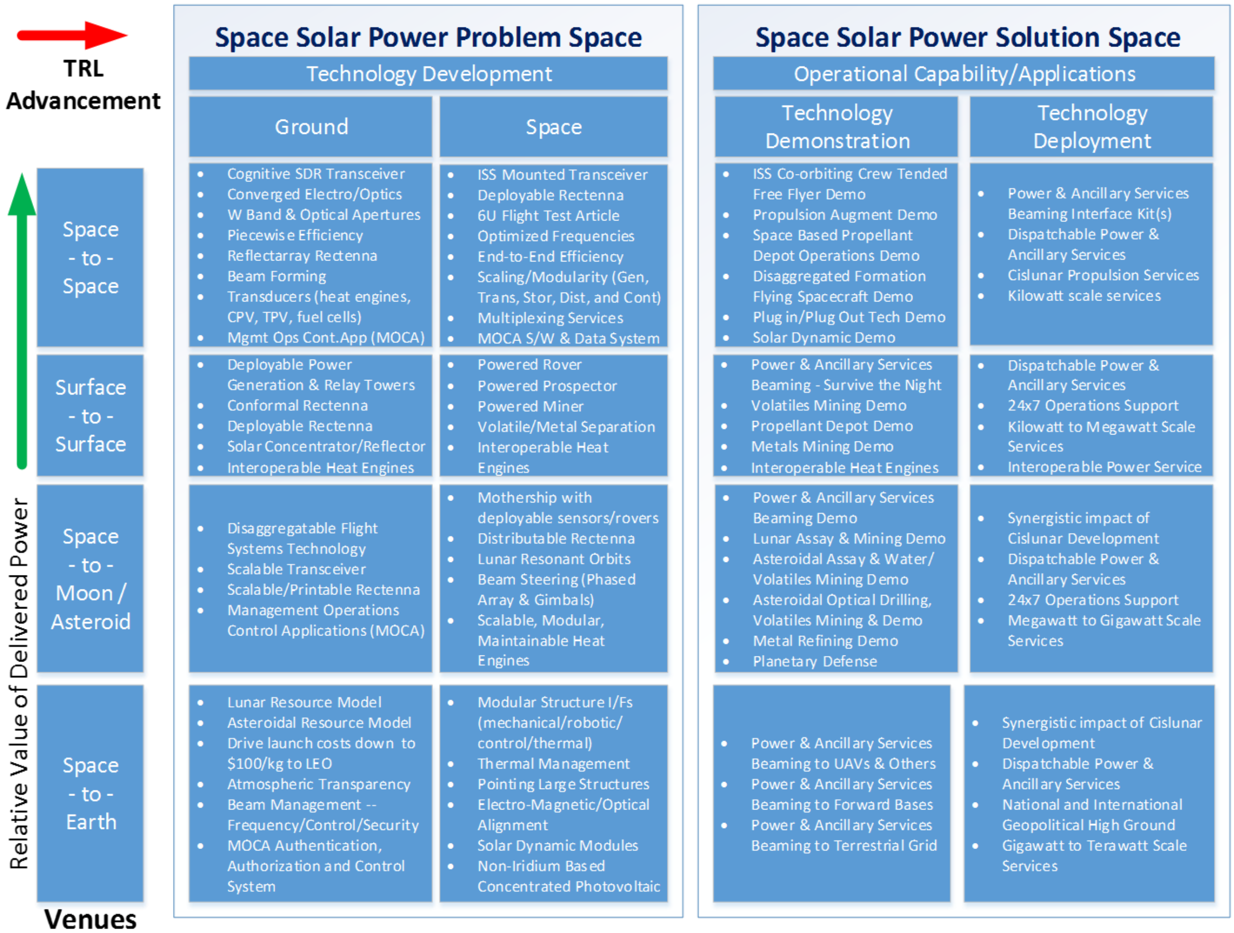


Figure 1 – Space Solar Power Challenge Matrix

The visualization of the Challenge Matrix proved to be a challenge in and of itself. As shown in Figure 2 – Challenges of Power and Ancillary Services Beaming. By showing the transitions from ground to space technology development and testbed work in the Space-to-Space venue leading to the subsequent technology demonstration and deployment of matured systems. Then building on that infrastructure to realize Surface-to-Surface systems, Space-to-Moon/Asteroid, and Space-to-Earth applications. While the applications development starts out as a serial mission development arch the opportunities for parallel development leveraging any achievable synergies should prove cost effective to realize at the earliest opportunity. The combination of the visualization, the narrative description of the key considerations, key attributes, and the Challenge Matrix, as well as the detailed analytical papers and presentations has successfully grown the community of interest in this body of work.

VI. SSPB MISSION PROGRAMMATIC HISTORY

The Space-to-Space Power Beaming (SSPB) mission has evolved from a basic proof-of-concept testbed offering only measurable delivered power proposed to leverage the NASA Space Communications and Navigation (SCaN) testbed on ISS in cooperation with NASA HQ & NASA GRC. Due to mission development review work that NASA required this approach was eventually obviated by ground analysis and test data from other non-space applications.

Going forward the NASA ISS condition of satisfaction for support of the SSPB commercial mission established by the ISS Program Director was the engagement of the ISS U.S. National Lab payload broker the Center for the Advancement of Science in Space (CASIS) and the NASA Research Announcement (NRA) for ISS Technology Development rolling procurement out of NASA JSC Code OZ. Based on the available resources XISP-Inc engaged CASIS first but they were unable and/or unwilling to go forward with the mission without the advice and consent of NASA. Obtaining that advice and consent required a white paper process and a subsequent mission development effort which culminated in the successful submittal of compliant proposal for evaluation under the NRA.

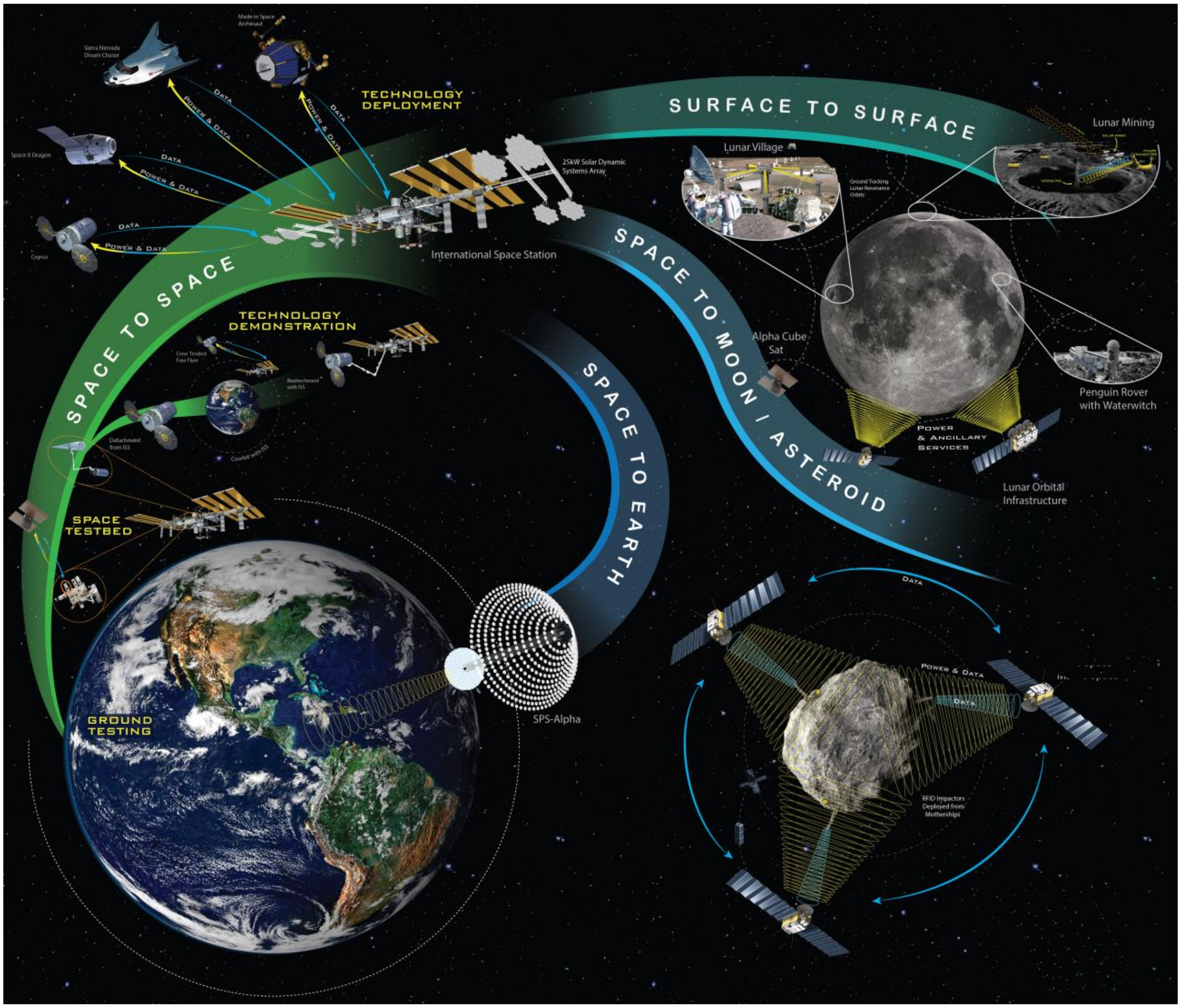


Figure 2 – Challenges of Power and Ancillary Services Beaming

NASA 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 is relevant to NASA's exploration goals and reflects the involvement of a team with appropriate experience. However, based upon the details of the proposal and the review of it performed by multiple organizations across the agency, we are not able to fund the proposed effort at this time. – George Nelson, NASA Code OZ NRA Manager March 2017"

On further review, since the mission was intended as a commercial one it was referred to CASIS with the advice and consent of NASA Code OZ for further mission development support as they saw fit.

The XISP-Inc SSPB mission development work has continued with CASIS, now known as the U.S. National Lab, as a potential ISS resource allocation partner but not as funding resource.

Subsequently, NASA has published an ISS Commercial Utilization Policy which sets forth a fixed price schedule of resources and services available for transportation to the ISS and for operations on and proximate to it. This affords a basis for developing business plans with a high degree of cost and programmatic certainty to flight and operations, while not precluding government involvement (by NASA or any number of other agencies) in some form of Public/Private Partnership which could reduce scheduled costs. At this point, the XISP-Inc commercial mission development efforts are focused on this path to flight.

VII. SSPB MISSION OVERVIEW

The Space-to-Space Power Beaming (SSPB)

- Unbundle/disaggregate spacecraft electrical power systems
- Provide beamed power and ancillary services as a utility
- Support further development of power beaming technology
- SSPB mission divided into three linked phases: Technology Development, Demonstration, and Deployment (TD^3) intended to bridge the technology “valley of death”
- TD^3 mission defines a civilian non-weapons use space solar power
- Addressing real and perceived cost, schedule, and technical risks associated with Space Solar Power and ancillary services beaming
- Addressing multiple venues including: Space-to-Space, Space-to-Alternate Surfaces, as well as the potential for Space-to-Earth.
- Effort will lead to use of beamed energy to support:
- sustained ISS co-orbiting free-flyer operations,
- Enhanced power requirements/augmented propulsion,
- loosely coupled modular architecture, and
- new cluster architectures

Figure Y—SSPB Functional Block Diagram provides an outline of the primary interfaces that are integral to the mission.

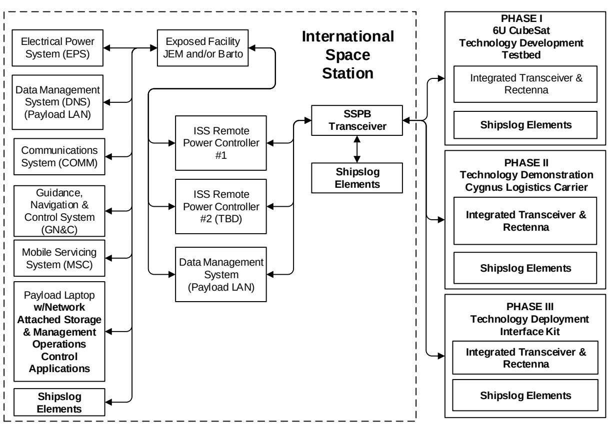


Figure Y – SSPB Functional Block Diagram

Figure X – Phase I & Follow on Concept of Operations lays out the baseline concept of operations for the SSPB mission.

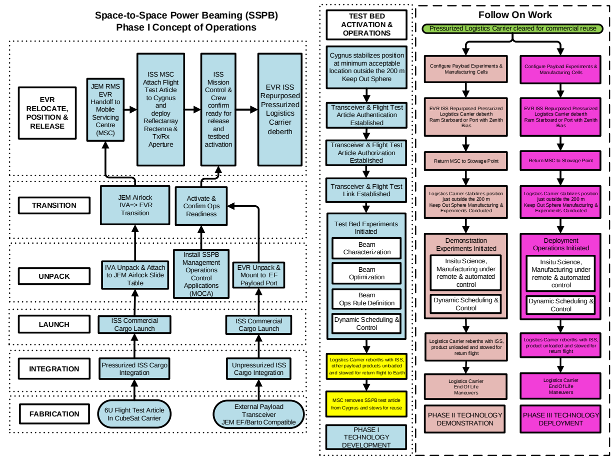


Figure X – Phase I & Follow on Concept of Operations

<u>SSPB Phase I - Technology Development Components</u>

- Multi-band receiving antennas (rectennas) (Ka, W, and Optical)
- Optimized Multi-band transceivers (Ka, W band, and Optical)
- Multi-band phased array transmission apertures
- Radiant energy beaming control and safety interlock system
- Water based thrusters for propulsion/active attitude control
- Power/Data/Communications/Navigation/Time Multiplexing
- Power and allied utility waveforms for Software Defined Radios
- Converged Radio Frequency & Optical SDR electronics

<u>SSPB Phase II - Technology Deployment Components</u>

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

<u>SSPB Phase III - Technology Deployment Components</u>

- ISS Co-orbiting Radiant Energy Beaming (200 m to 1 km)
- 6U Cubesat MSC released test with optimized transmitter & rectenna
- NGIS Cygnus pressurized logistics carrier test with optimized transmitter & rectenna
- Made In Space manufacturing protoflight rectenna (proposed)

- Evolved/scaled systems will address other markets for power and ancillary utilities delivery in LEO, MEO, HEO, GEO, Libration/Trajectory Waypoints, Lunar Orbits, and the Lunar Surface.
- Power and allied utilities delivery will progress as systems are fielded.

➔Emergency ➔ Servicing ➔Augment ➔Backup ➔Primary.

Based on the parsimonious use of available ISS resources the SSPB ISS transceiver system design now incorporates the JEM Exposed Facility Standard Payload Interface, the Bartolomeo Oceaneering Space Systems Gold Interface, and the SSRMS Power/Data Grapple Fixture, and SPDM compatible OTCM interfaces where appropriate. The baseline SSPB mission would see the SSPB ISS mounted transceiver first deployed on the Bartolomeo exposed facility where the input power is maximum is less than 1 kW but it is not over subscribed. When resource allocations allow for it the SSPB transceiver can then be relocated to the JEM Exposed Facility when up to 6 kW input power can be provided if the resource allocation is made available.

The flight test article is designed to accommodate the hybrid solar panel, rectenna, and communications antenna shown schematically in Figure X – Advanced multi-layer reflectarray panels.

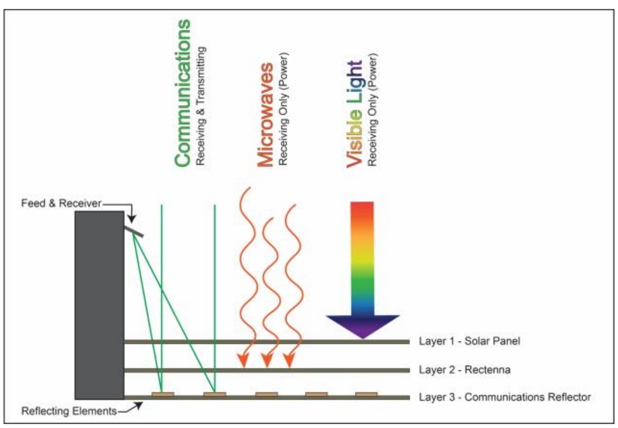


Figure X – Advanced multi-layer reflectarray panels

The promise of power beaming as it relates to the SSPB mission and applications is drawn out by comparison between achievable power densities and the solar constant (I_{sc}) Figure A – Comparing Beaming Power Density and the Solar Constant. At the low end of Ka Band (~26.5 GHz) the SSPB achievable power density would be approximately an order of magnitude less than I_{sc}. At the high end of Ka Band (~36 GHz) the SSPB achievable power density would be approximately twice I_{sc}. However, in W band (~95 GHz) the SSPB achievable power density would be approximately an order of magnitude higher than I_{sc}. While there are many more aspects of system efficiency/performance to consider this table make it clear that there is some value to found in power beaming.

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

$$p_d = \frac{A_t P_t}{\lambda^2 D^2}$$

p_d is the power density at the center of the receiving location
P_t is the total radiated power from the transmitter
A_t is the total area of the transmitting antenna
λ^2 is the wavelength squared
D^2 is the separation between the apertures squared

Figure A – Comparing Beaming Power Density and the Solar Constant.

In cases where the rectenna aperture is not small in proportion to the transmitter aperture, transmitter power levels are high, and the frequency is high, power received (Pr) calculations break down using the far-field equations. Accordingly, the Pr is calculated using the collection efficiency method instead of the far-field equations.

<u>SSPB Phase Advancement Mission</u>

An alternative approach has been defined which advances the work directly to the support of a pressurized logistics carrier that would operate in a co-orbiting free-flyer mode with ISS and other LEO objects making use of a robotically deployable functional equivalent of the six U cubesat power and ancillary services beaming test article already defined. The test article would be collected at the ISS, the pressurized logistics carrier would deploy for a co-orbiting payload mission, and then return to ISS with the payload research products and the power and ancillary services beaming test article will be returned to its stowage point. See Figure X – SSPB Phase I Concept of Operations Cygnus Optimized.

<u>VIII. PROBLEM / SOLUTION SPACE BLOCK DIAGRAMS</u>

The overall problem and solution space that power beaming is part of is the sustainable power generation, storage, and distribution is outline in block diagram shown in Figure 8. The diagram is overlaid with a color key indicating if the TRL for the technologies involved are considered to be at a tipping point, susceptible to synergistic improvement, or are at stable TRL point representing mature technology.

The internal and external interfaces between the block elements can be further detailed based on first principles physics an example of which is shown in Figure 9.

From the basic interface block diagram an optimized block diagram can be designed an example of which is shown in Figure 10.

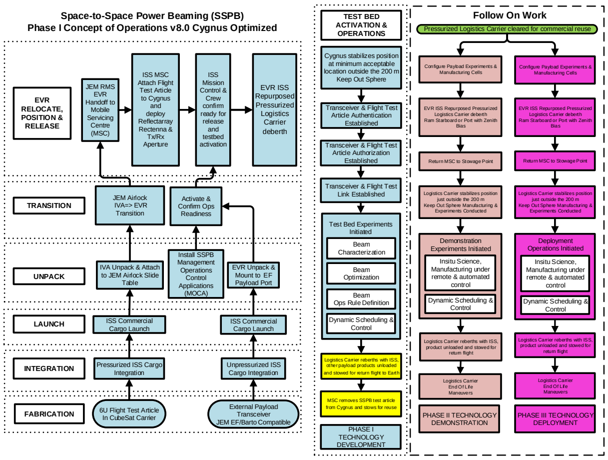


Figure X – SSPB Phase I Concept of Operations Cygnus Optimized

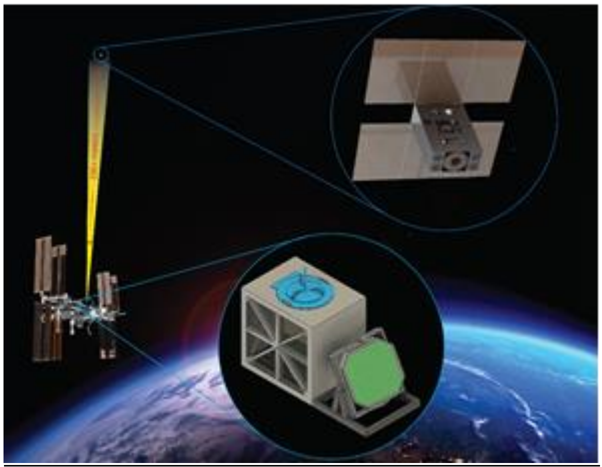


Figure 2 – SSPB Mission Overview

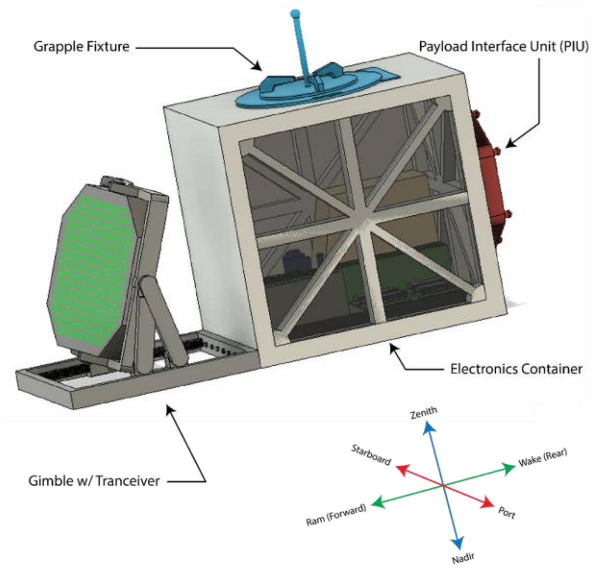


Figure 3 – SSPB Transceiver Preliminary Design

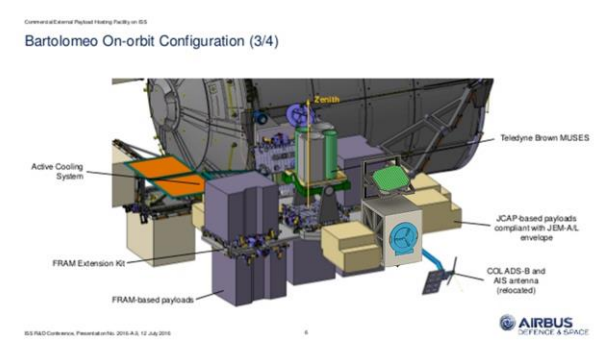


Figure 4 – AIRBUS Bartolomeo Exposed Facility Accommodations

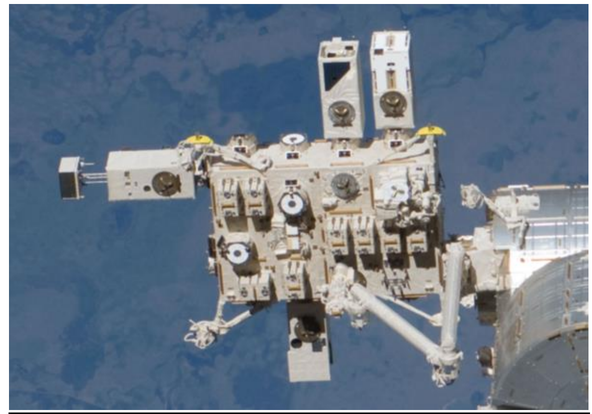


Figure 5 – SSPB Transceiver Preliminary Design

Figure 6 –Northrop Grumman Cygnus Logistics Module and Co-orbiting Free Flyer Candidate

Figure 7 –SpaceX Dragon Logistics Module and Co-orbiting Free Flyer Candidate

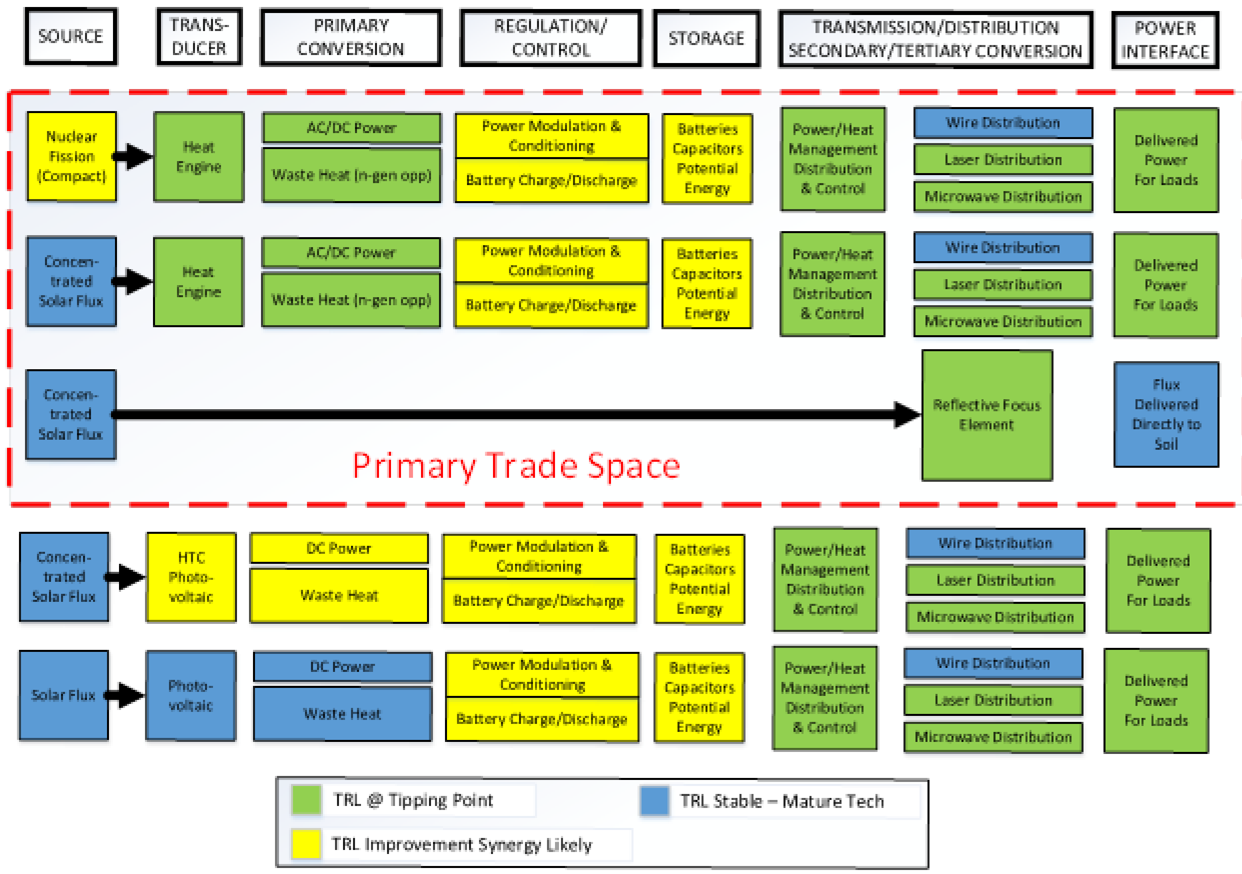


Figure 8 – Sustainable Power Generation, Storage, and Distribution

<u>Power Generation</u>

- Process Heat Options (high, medium, low, and rejected)
- Stored Heat (thermal mass, phase change)
- Stored Power (batteries, fuel cells hydrogen, oxygen, water, ice)
- Storage/buffering of power is appropriate at the primary conversion point, at the crater floor substation, and/or at the actual electrical load point of use.
- Allocation of these capabilities locations needs to be optimized to assure normal continuous operations as well as the ability to deal with contingency shut down situations.
- Reversible fuel cell from the Space Shuttle is functionally equivalent to the ISRU electrolysis unit enabling interoperability / synergy for dispatchable power

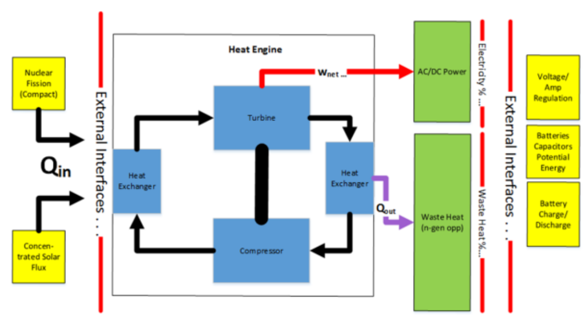


Figure 9 – Brayton Cycle Heat Engine Block Diagram (Simple)

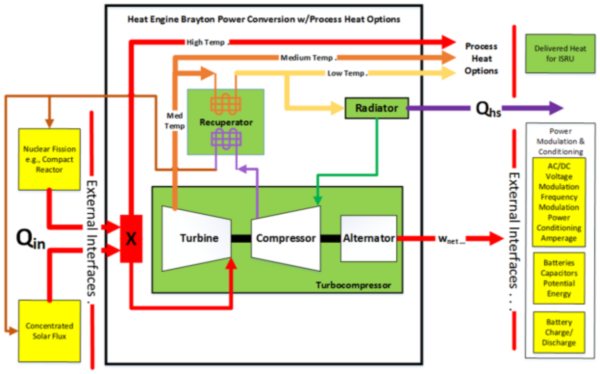
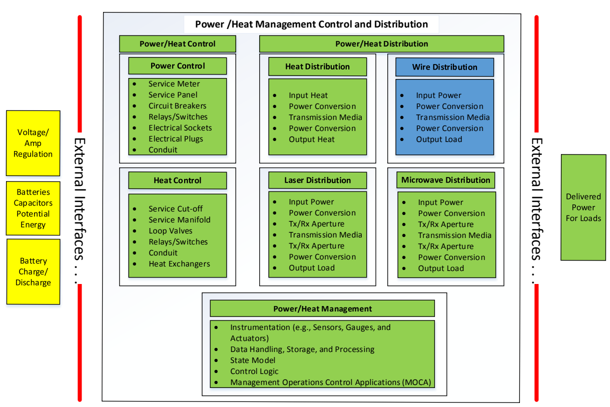


Figure 10 – Brayton Cycle Hear Engine Block Diagram w/Process Heat Options

Power Storage

- Process Heat Options (high, medium, low, and rejected)
- Stored Heat (thermal mass, phase change)
- Stored Power (batteries, fuel cells hydrogen, oxygen, water, ice)
- Storage/buffering of power is appropriate at the primary conversion point, at the crater floor substation, and/or at the actual electrical load point of use.
- Allocation of these capabilities locations needs to be optimized to assure normal continuous operations as well as the ability to deal with contingency shut down situations.
- Reversible fuel cell from the Space Shuttle is functionally equivalent to the ISRU electrolysis unit enabling interoperability / synergy for dispatchable power

Power Transmission & Distribution



IV. OTHER SOLUTION SPACE EXAMPLES

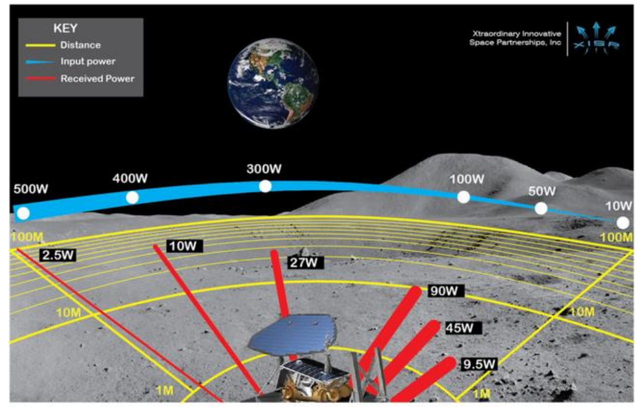


Figure 11 - Surface-to-Surface Power & Ancillary Services Beaming

Figure 13 – Advanced Lunar Power & Ancillary Services Beaming Infrastructure

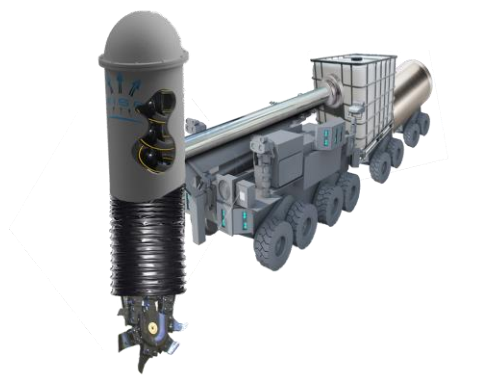


Figure 14 – WaterWitch Lunar Regolith Processing

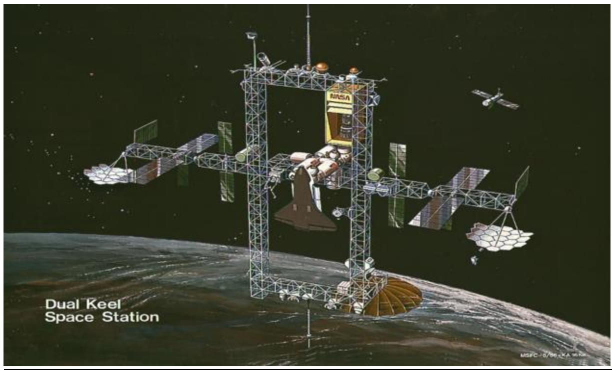


Figure 15 - Early Space Station Design w/Solar Dynamic

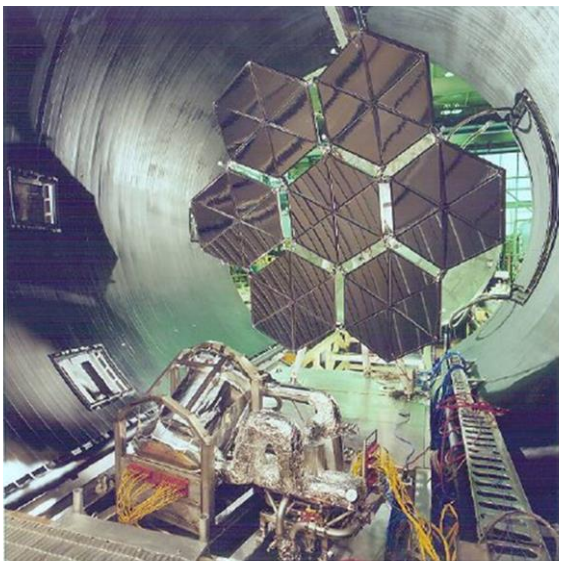


Figure 16 - LaRC/GRC 2kW Solar Dynamic Test

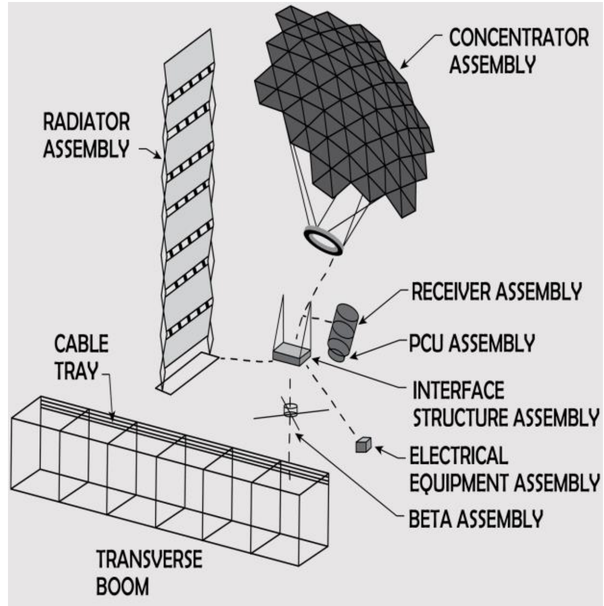


Figure 17 - Solar Dynamic Components

IX. CONCLUSION

The physics of near field/ far field energy propagation are well understood areas of art and practice. However, the use of radiant energy to transfer: power, data, force, &/or heat, either directly and/or by inducing near field effects at a distance, are not well understood. Moreover, there is very limited engineering knowledge base of practical applications. Accordingly, this is applied engineering work, (a.k.a. technology development), not new physics. To optimize beaming applications we need to better understand how each of the components of radiant energy can be made to interact in a controlled manner.

Radiant energy components include:
- Electrical
- Magnetic
- Linear & Angular Momentum
- Thermal
- Data

There are potential direct and indirect uses for each beam component. Use of any combination of these components has implications for all spacecraft systems (e.g., power, data, thermal, communications, navigation, structures, GN&C, propulsion, payloads, etc.)

In theory, the use of the component interactions can enable:
- Individual knowledge of position and orientation
- Shared knowledge loose coupling /interfaces between related objects
- Near network control (size to sense/proportionality to enable desired control)

- Fixed and/or rotating planar beam projections
- Potential for net velocity along any specified vector

In theory, there is no difference between theory and practice – but in practice, there is.

– Jan L.A. van de Snepscheut
computer scientist

Additional challenges that must be addressed include:

- Economics
  - Map the financing to terrestrial electrical power and ancillary services utility analog that just happens to be in space.
  - Each addressable market has different fundamental figures of merit.
- Public/Private Partnerships
  - Drawing out the confluence of interests that can support substantive agreements
- Geopolitical
  - Make International Cooperation/Collaboration real.

VI. REFERENCES

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10. Barnhard, Gary Pearce – "Mission Development Forum" – International Space Development Conference (ISDC 2011) Huntsville, AL – Facilitator & Systems Engineering Review Panelist (May 2011)
11. Barnhard, Gary Pearce – "Turning good ideas into gold - blazing a trail through the technology development valley of death" – International Space Development Conference (ISDC) 2012 -- Presentation and Panel discussion Washington, DC (May 26, 2012)
12. Barnhard, Gary Pearce -- "XISP - Xrosslink Internet Services Protocol" -- International Space Development Conference (ISDC 2012) Washington, DC -- presentation and panel discussion May 26, 2012.
13. Barnhard, Gary Pearce – "Commercial Delay Tolerant Pervasively Networked Point-of-Presence Gateway System for ISS" -- AAS/NASA/CASIS 1st Annual ISS Research and Development Conference Denver, CO – Presentation June 26, 2012
14. Barnhard, Gary Pearce – "Commercial Delay Tolerant Pervasively Networked Point-of-Presence Gateway System for ISS", AAS 12-670, Proceedings of the 1st ISS Research and Development Conference, Results and Opportunities – The Decade of Utilization Vol 114 Science and Technology Series, AAS 2013
15. Barnhard, Gary Pearce, presentation – "Suspending Disbelief - Unbundling Space Power Systems to foster applications of Space-to-Space Power Beaming", International Space Development Conference (ISDC) 2013, San Diego, CA May 25, 2013
16. Barnhard, Gary Pearce – "Space-to-Space/Surface Power Beaming", AAS / NASA / CASIS 2nd Space Station Users Conference, Denver, CO – Poster session July 16, 2013
17. Barnhard, Gary Pearce, poster session – "Interoperable Network Communications Architecture", AAS / NASA / CASIS 2nd Space Station Users Conference, Denver, CO – Poster session July 16, 2013
18. Barnhard, Gary Pearce – "Suspending Disbelief -- Unbundling Space Power Systems to foster applications of Space-to-Space Power Beaming", IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE) Space Based Solar Power Workshop, Baltimore, MD – Presentation November 8, 2013
19. Barnhard, Gary Pearce, Associate Fellow, AIAA – "Space-to-Space Beamed Power", Space Solar Power (SSP 2014) Kobe, Japan -- Presentation April 15, 2014
20. Barnhard, Gary Pearce – "Space-to-Space Power Beaming" International Space Development Conference (ISDC) 2014, Los

Angeles, CA – Presentation Space Solar Power Track May 15, 2014
21. Barnhard, Gary Pearce – "Unbundling Space Solar Power Systems", 3rd ISS Research and Development Conference Chicago, IL – Poster session June 2014
22. Barnhard, Gary Pearce – "Interoperating Network Communications Architecture (INCA)", 3rd ISS Research and Development Conference Chicago, IL – Poster session June 2014
23. Barnhard, Gary Pearce -- "Unbundling Space Solar Power Systems to foster applications of Space-to-Space Power Beaming ", International Astronautical Conference (IAC) 2014, Toronto, Canada -- Presentation and Paper September 29, 2014 IAC-14-C3.1.9
24. Barnhard, Gary Pearce – "Interoperable Network Communications Architecture", International Astronautical Conference (IAC) 2014, Toronto, Canada -- Presentation and Paper September 29, 2014 IAC-14-B2.3.6
25. G.P. Barnhard – "Space to Space Power Beaming -- A Commercial Mission to Unbundle Space Power Systems to Foster Space Applications", AIAA 21st Improving Space Operations Support Workshop, Pasadena, CA – Presentation May 6, 2015
26. Barnhard, Gary Pearce; Dahlstrom, Eric; Chew, Ethan – "Halfway to Anywhere" - AIAA 21st Improving Space Operations Support Workshop, Pasadena, CA – Presentation May 6, 2015
27. Barnhard, Gary Pearce – "Interoperable Network Communications Architecture" - AIAA 21st Improving Space Operations Support Workshop, Pasadena, CA – Presentation May 6, 2015
28. Barnhard, Gary Pearce – "Space Solar Power : Strategies for Architecting the Future" International Space Development Conference (ISDC) 2015, Toronto, Canada – Presentation Space Solar Power Track May 21, 2015
29. Barnhard, Gary Pearce – "Space to Space Power Beaming -- A Commercial Mission to Unbundle Space Power Systems to Foster Space Applications" - International Space Development Conference (ISDC) 2015, Toronto, Canada – Presentation Space Solar Power Track May 22, 2015
30. Barnhard, Gary Pearce – "Evolvable Communications Infrastructure on ISS and Interoperating Flight/Ground Systems" - International Space Development Conference (ISDC) 2015, Toronto, Canada – Presentation Lunar Workshop May 23, 2015
31. Barnhard, Gary Pearce, "Unbundling Space Solar Power Systems" Future In Space Operations (FISO) Colloquia – Presentation
32. Barnhard, Gary Pearce, "Unbundling Space Solar Power Systems" - 4th Annual ISS R&D Boston, MA – Poster Session July 2015
33. Barnhard, Gary Pearce, "Unbundling Space Solar Power Systems" - IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE) 2015Space Based Solar Power Workshop, Orlando, FL – Presentation December 14, 2015
34. G.P. Barnhard, "Commercial Space-to-Space Power Beaming Mission – Accelerating Incremental Evolution", International Space Development Conference (ISDC) 2016, San Juan, PR – Presentation Space Solar Power Track May 20, 2016
35. Barnhard, Gary Pearce – "Interoperable Network Communications Architecture" & "Alpha Cubesat" - International Space Development Conference (ISDC) 2016, San Juan, PR – Presentation
36. Barnhard, Gary Pearce; "Mission Operations Control Applications (MOCA) to Advanced Vision and Task Area Recognition (AVaTAR)" – Presentation Future In Space Operations Colloquia June 22, 2016
37. Barnhard, Gary Pearce; Dahlstrom, Eric; "Halfway to Anywhere Cis-Lunar and Deep Space Cubesats Missions From ISS" AAS/CASIS/NASA 5th Annual International Space Station Research and Development Conference 2016 San Diego, CA – Presentation July 13, 2016
38. Barnhard, Gary Pearce; "Interoperating Network Communications Architecture - A technology development Mission to extend commercial networks to space and more" AAS/CASIS/NASA 5th Annual International Space Station Research and Development Conference 2016 San Diego, CA – Presentation September 13, 2016
39. G.P. Barnhard, D. Faber, "Space-to-Space Power Beaming – A Commercial Mission to Unbundle Space Power Systems to Foster Space Applications", AAS/CASIS/NASA 5th Annual International Space Station Research and Development Conference 2016 San Diego, CA – Presentation July 12, 2016
40. Barnhard, Gary Pearce; "Mission Operations Control Applications" poster session presentation at the AAS/CASIS/NASA 5th Annual International Space Station Research and Development Conference 2016 San Diego, CA – July 13, 2016

41. G.P. Barnhard, D. Faber, "Space-to-Space Power Beaming - A Commercial Mission to Unbundle Space Power Systems to Foster Space Applications", AIAA Space 2016 Long Beach, California – Paper and Presentation September 12, 2016
42. Barnhard, Gary Pearce; "Halfway to Anywhere -- Cislunar and Deep Space Cubesats Missions From ISS", AIAA Space 2016 Long Beach, CA – Paper and Presentation September 13, 2016
43. Barnhard, Gary Pearce; "Mission Operations Control Applications -- A commercial mission to extend, validate, and apply the NASA MCT toolkit for ISS experiment control", AIAA Space 2016 Long Beach, CA – Paper and Presentation September 13, 2016
44. G.P. Barnhard, D. Faber, "Space-to-Space Power Beaming - A Commercial Mission to Unbundle Space Power Systems to Foster Space Applications", IAC 2016 Guadalajara, Mexico -- presentation and paper September 27, 2016
45. Barnhard, Gary Pearce; "Interoperating Network Communications Architecture - A technology development Mission to extend commercial networks to space and more" IAC 2016 Guadalajara, Mexico -- presentation and paper September 29, 2016
46. Barnhard, Gary Pearce – "Energy Cislunar Market Place Workshop Report: Orchestrating the Technology Development, Demonstration, and Deployment (TD^3) Missions needed to foster electrical utilities for Cislunar space, Space Symposium, Colorado Springs, CO – Presentation April 6, 2017
47. Barnhard, Gary Pearce – "ISS Space-to-Space Power Beaming TD^3 Mission" - International Space Development Conference (ISDC) 2017, Space Solar Power Symposium, St. Louis, MO – Presentation May 25, 2017.
48. Barnhard, Gary Pearce; Blair, Brad; Faber, Daniel – "Lunar Power & Light Company -- Orchestrating the Technology Development, Demonstration, and Deployment (TD^3) Missions needed to foster electrical utilities for Cislunar space." - International Space Development Conference (ISDC) 2017, Space Solar Power Symposium, St. Louis, MO – Presentation May 26, 2017.
49. Barnhard, Gary Pearce; Faber, Daniel – "XISP-Inc Commercial ISS Space-to-Space Power Beaming Technology Development, Demonstration, and Deployment (TD^3) Mission" – Paper Written for AIAA Space 2017, Orlando, Florida. Republished in NSS Space Settlements Journal, December 2017.
50. Barnhard, Gary Pearce – "XISP-Inc Commercial ISS Space-to-Space Power Beaming Technology Development, Demonstration, and Deployment (TD^3) Mission" – IEEE Wireless in Space Extreme Environments (WiSEE) 2017, Space Solar Power Workshop, Montreal, Canada. – Presentation October 10, 2017.
51. Anzaldua, Al; Barnhard, Gary; Dunlop, David; Phipps, Claude – "A path to a commercial orbital debris cleanup, power-beaming, and communications utility, using technology development missions at the ISS", The Space Review November 6, 2017
52. Barnhard, Gary Pearce – "XISP-Inc Commercial ISS Space-to-Space Power Beaming Technology Development, Demonstration, and Deployment (TD^3) Mission", 20th Annual DE S&T Symposium 2018 Power Beaming Metrology, Safety And Applications Session Challenges of Power Beaming Panel Input, Oxnard, California – Presentation & Poster Session February 27, 2018
53. Barnhard, Gary Pearce – "Lunar Power & Light Company: Orchestrating the Technology Development, Demonstration, and Deployment (TD^3) Missions needed to foster an electrical power and ancillary services utility for Cislunar space", International Solar Power Satellite Symposium & Workshop (SSP-2018) ISDC 2018, Los Angeles, California – Presentation May 23, 2018
54. Barnhard, Gary Pearce – "XISP-Inc Commercial ISS Space-to-Space Power Beaming Technology Development, Demonstration, and Deployment (TD^3) Mission", International Solar Power Satellite Symposium & Workshop (SSP-2018) ISDC 2018, Los Angeles, California – Presentation May 24, 2018
55. Barnhard, Gary Pearce, Potter, Seth Douglas "Challenges of Space Power Beaming: Forging production services from the technology development trade space ", AIAA Space 2018 Orlando, Florida – Paper and Presentation September 19, 2018
56. Barnhard, Gary Pearce, Potter, Seth Douglas "Challenges of Space Power Beaming: Forging production services from the technology development trade space ", IAC-18-C3.2.4, IAC 2018 Bremen, Germany – Paper and Presentation October 2, 2018

57. Barnhard, Gary Pearce, "Challenges of Space Power Beaming & Ancillary Services", Lunar Exploration Analysis Group, Survive and Operate Through the Lunar Night Workshop, November 13, 2018 Columbia, MD – Poster Session
58. Barnhard, Gary Pearce, "Challenges of Space Power Beaming: Forging production services from the technology development trade space", IEEE Wireless in Space and Extreme Environments (WiSEE) 2018 Space Solar Power Workshop Huntsville, AL December 11, 2018
59. Barnhard, Gary Pearce, "Space Solar Power & ancillary services Beaming as enabling infrastructure", Space Solar Power Symposium ISDC 2019, Washington, DC – Presentation June 5, 2019
60. Barnhard, Gary Pearce, "Surface-to-Surface customers", Space Solar Power Symposium ISDC 2019, Washington, DC – Presentation June 5, 2019
61. Barnhard, Gary Pearce, "Surface-to-Surface Power Beaming", Lunar ISRU 2019 – Developing a New Space Economy through Lunar Resources and their Utilization, Columbia, Maryland July 15-17, 2019 – Poster Session
62. Barnhard, Gary Pearce; Blair, Brad, "Solar Dynamic Systems: A Path to a Lunar Power and Light Company", Lunar ISRU 2019 – Developing a New Space Economy through Lunar Resources and their Utilization, Columbia, Maryland July 15-17, 2019 – Poster Session
63. Baiden, Greg; Barnhard, Gary Pearce; Blair, Brad, "Lunar Production Drilling Using WaterWitch", Lunar ISRU 2019 – Developing a New Space Economy through Lunar Resources and their Utilization, Columbia, Maryland July 15-17, 2019 – Poster Session

I. MAJOR HEADINGS

Major headings are capitalized, underlined and centred in the column.

Subheadings

Subheadings are underlined and placed flush on the left hand margin of the column.

Sub-subheadings

Sub-subheadings are underlined and indented

II. STYLE GUIDE

II.I Acronyms

Always use the full title followed by the acronym to be used.

II.II References

List and number all the bibliographical references at the end of the full text, in the order of appearance[1].

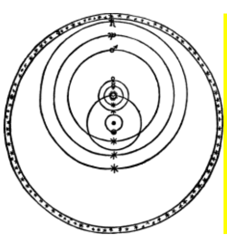
II.III Equation Numbers

When numbering equations, enclose numbers in brackets and place flush right with the right hand margin of the column.

$$\vec{F}_{12} = -G \cdot \frac{m_1 \cdot m_2}{\left\|\vec{r}_2 - \vec{r}_1\right\|^2} \cdot \hat{u}_{12} \qquad [1]$$

II.VI Illustrations and Captions

It is important to remember that all artwork, captions, figures, graphs and tables will be reproduced exactly as you submitted them. (**Company logos** and **identification numbers** are not permitted on your illustrations).



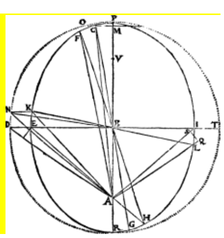


Fig. X: Title of the figure, left justified, subsequent text indented. Place figures at the top or bottom of a column wherever possible, as close as possible to the first references to them in the manuscript. Restrict them to single-column width unless this would make them illegible.

II.V Graph Lines, Drawings and Tables

Use black ink on white manuscript and position to fit within one of the columns on the page, and ensure that they remain still readable.

Tables with a moderate amount of information should be positioned within one column. Tables, graphs or pictures with large amounts of information may extend across two columns.

	Venus	Earth	Mars	Jupiter
M/M_E	0.82	1	0.11	317.89
e	0.007	0.017	0.093	0.048
R (AU)	0.7233	1	1.524	5.203
i (deg)	3.40	0	1.85	1.30
T (years)	0.62	1	1.88	11.86

Table X: Title of table, left justified, subsequent text indented. Heading centred. Do not use vertical lines within the table; use horizontal lines only to separate headings from table entries

II.VI Captions, Graph Axes, Legends

Captions, graph axes, legends, etc. should be large enough to remain readable.

II.VII Footnotes, Symbols and Abbreviations

Footnotes should be cited using symbols in this order: *, t, :t, §, <J[, **, tt, :t:t. Use only standard symbols and abbreviations in text and illustrations.

II.VIII Page Numbers

Indicate page numbering at the bottom of each page.

[1] IAF Secretariat, 2012, Instructions to the Authors for the 63rd International Astronautical Congress – Naples