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EVOLUTION OF ISS AS TECHNOLOGY DEVELOPMENT, DEMONSTRATION, AND DEPLOYMENT (TD^3) INFRASTRUCTURE TO SUPPORT COMMERCIALIZATION OF LOW EARTH ORBIT AND BEYOND

Abstract

The commercialization concepts, business plans, and viability of habitable platforms in Low Earth Orbit (LEO) are critically dependent on an evolvable infrastructure that will provide the necessary utilities and ancillary services to accommodate addressable markets for the International Space Station (ISS) directly as well as for free-flying spacecraft and their aggregations. Markets for the above are, and will be, driven by explorations, operations, and applications that will be run by a combination of government, international partner, non-profit, and commercial entities. Orchestrated extraordinary innovative public/private partnerships that leverage existing and evolving space and ground infrastructure, commercial investments, academic and non-profit resources, and intergovernmental agreements to blaze a roadmap to the commercialization of LEO are essential for the cost-effective commercialization of LEO and beyond. The authors postulate that these markets are best developed by the support of the evolution of ISS as a Technology Development, Demonstration, and Deployment (TD^3) infrastructure to support the commercialization of LEO and beyond. By facilitating the ISS' ability to serve as LEO commercialization infrastructure that can foster the definition, execution, and accomplishment of a pipeline of TD^3 missions, the synergistic effects can be maximized along with the other modes (e.g., science laboratory, operations center, transportation node, etc.) of utilization. This provides a <u>foundation for progress reporting on the research, identifying, and articulating</u> the qualitative and quantitative narratives for TD^3 missions detailing how to stimulate the private demand for commercial LEO services in order to sustain the long-term LEO addressable markets with primarily non-NASA commercial revenue. For each TD^3 mission, the combination of "technology development push," "mission requirements pull," and "commercial applications/infrastructure playout" will be researched and evaluated. This paper lays out a framework for an iterative and recursive process to examine every ISS system and element for opportunities for stand-alone and integrated evolution to support multiple applications consistent with the context of the defined TD^3 missions.

I. COMMERCIALIZATION AND TECHNICAL CONCEPT

The commercialization concepts, business plans, and viability of habitable platforms in Low Earth Orbit (LEO) are critically dependent on evolvable infrastructure that will provide the necessary utilities and ancillary services to accommodate addressable markets for the International Space Station (ISS) directly as well as for free-flying spacecraft and their aggregations. The ISS is at its foundation evolvable infrastructure (see Figure 1).

Markets for the above are and will be driven by explorations, operations, and applications that will be run by a combination of government, international partner, non-profit, and commercial entities. Orchestrated extraordinary innovative public/private partnerships that leverage existing and evolving space and ground infrastructure, commercial investment, academic and non-profit resources, and intergovernmental agreements to blaze a roadmap to commercialization of LEO are essential to the cost effective commercialization of LEO and beyond.

Figure 1 - Early Space Station Design w/Solar Dynamic

This proposed study postulates that these markets are best developed by the support of the evolution of ISS as Technology Development, Demonstration, and Deployment (TD^3) infrastructure to support the commercialization of LEO and beyond. By facilitating the ISS' ability to serve as a LEO commercialization infrastructure that can foster the definition, execution, and accomplishment of a pipeline of TD^3 missions, the synergistic effects can be maximized along with the other modes of utilization. This study will research, identify, and articulate the qualitative and quantitative narratives for TD^3 missions detailing how to stimulate the private demand for commercial LEO services in order to sustain the long-term LEO addressable markets with primarily non-NASA commercial revenue.

This study will assume the ISS Transition Report guidance to be considered and the articulation of NASA's long-term LEO needs as a given. For each TD^3 mission, the combination of "technology development push," "mission requirements pull," and "commercial applications/infrastructure playout" will be researched and evaluated. In addition, every ISS distributed system and element, as well as other cooperating infrastructure elements and proposed commercial elements, will be examined for opportunities for stand-alone and integrated evolution to support multiple applications consistent with the context of the defined TD^3 missions.

XISP-Inc is a For-Profit corporation focused on the creation and execution of TD^3 missions intended to bridge the technology development "valley of death". XISP-Inc has been working on commercial TD^3 mission development under a Non-reimbursable NASA Space Act Agreement in cooperation with HEOMD (AESD & SCaN). XISP-Inc proposes to extend the work that stemmed from the intersection of the XISP-Inc commercial Space-to-Space Power Beaming mission development effort (currently being evaluated by the Center for the Advancement of Science In Space (CASIS) for ISS resource allocation and mission development investment), the ULA Cislunar Marketplace workshop initiative Energy subgroup presentation prepared and presented by XISP-Inc at the Space Symposium Cislunar workshop in 2017, and other XISP-Inc mission development efforts to advise and inform the proposed study effort. The intersections within the XISP-Inc mission set are shown in Figure 1 – XISP-Inc Evolving TD^3 Mission Set, and is outlined in narrative form below.

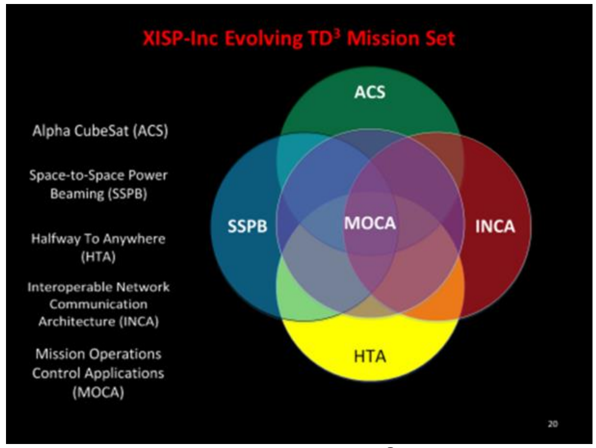

Figure 1 – XISP-Inc Evolving TD^3 Mission Set

Each of the XISP-Inc commercial missions identified has one or more defined objectives, and an envisioned commercial playout.

SSPB provides a TD^3 radiant energy beaming testbed, as well as electrical and ancillary services utilities, for ACS, HTA, INCA, and MOCA missions.

➔ Space-to-Space, Space-to-Alternate surface, and Surface-to-Surface Electrical Power and Ancillary Services utility for Cislunar space (i.e., from the Karman line at 100 km through to the surface of the Moon).

ACS provides a TD^3 spacecraft bus for HTA, INCA, MOCA, and SSPB missions

➔ Low cost configurable spacecraft for Earth facing, Cislunar infrastructure, and beyond Earth orbit applications.

HTA provides a TD^3 propulsion testbed and a trajectory insertion bus as well as alternate minimum energy trajectories and resonance orbits for ACS, INCA, MOCA and SSPB missions.

➔ ISS as a transportation node for low=cost, readily deployable Earth, Cislunar, and beyond Earth orbit mission support.

INCA provides a TD^3 web accelerator, QoS routing/pervasively networked gateway, multi-core thermally managed computer resources, Xlink protocol, and relay interface kits for ACS, HTA, MOCA, and SSPB missions.

➔ Communications & Navigation Utilities and interface kits for Earth facing, on-orbit, and space-facing mission support/networks.

MOCA provides TD^3 near–real-time state models, a mutable locus of control, and a virtual operations center for ACS, HTA, INCA, and SSPB missions.

➔ Facilitate crewed and tele-operated/shared control and autonomous in situ operations, reducing crew time required for experiments and increasing ISS productivity.

II. TD^3 MISSION TOP DOWN CONSIDERATIONS

To better understand each opportunity, each must be characterized in terms of:

- Sectors involved
- Products/Services to be offered, including the problems being solved
- Customers, including market demand and competition
- Supplier/Resources
- Transportation requirements
- Investment/R&D requirements, including value proposition, investor expectations
- Infrastructure requirements
- Regulation issues

For example, when examining the SSPB mission in more detail, the following solution space key considerations have been identified.

<u>Sectors</u>**:**

- International Governmental Consortia
- Government Consortia
- Government-Commercial Consortia
- Government-Not for profit Consortia
- Commercial Consortia

There are no unilateral sector options underway, planned, or envisioned. Even if there were it is not clear that other interested entities would let them abide. Accordingly, to maximize the probability of success a consortium of some form is required.

<u>Products/Services</u>**:**

Cislunar Electrical Utility -- “Lunar Power & Light Company”

- Earth-to-Earth Wireless Energy
- Earth-to-Space Wireless Energy
- Space-to-Earth Wireless Energy
- Space-to-Space Wireless Energy
- Space-to-Luna Wireless Energy
- Luna-to-Luna Wireless Energy
- Luna-to-Earth Wireless Energy
- Space-to-Asteroid Wireless Energy
- Space Power Generation (in situ)

<u>Product Catalog</u>

- Emergency Power
- Backup Power
- Auxiliary Power
- Primary Power
- Indirect/Direct Momentum Transfer
- Ancillary Services (Communications, Navigation, Telemetry & Control Data, Experiment Data, etc.)

<u>Problems to be Solved</u> (What problems does the customer have?)

- Physical constraints due to wires or structural connections
- Micro-gravity impacts due to crew and system motion
- Power generation, storage, and transmission system cross-sectional area, mass, complexity, environmental degradation, failure tolerance, and cost
- Fuel transportation systems and logistics, military convoy safety
- Systems survival during lunar night
- Operation in eclipsed and/or permanently shadowed regions
- Efficiency losses and equipment degradation due to Galactic Cosmic Rays (GCR), solar particle events, and radiation trapped by the Earth’s magnetic field,
- Space debris, atomic oxygen, dust, and other forms of environmental degradation
- Increasing world demand for energy and clean water

Ultimately what is needed is a Cislunar electrical utility that leverages what economies of scale can be identified and used to best advantage.

<u>Customers (Space and Earth facing):</u>

<u>Key Functions</u>

- ISS Co-orbiting & other LEO spacecraft
- Transportation Vehicles
- Propulsion Augment (resistojets, etc.)
- Debris Mitigation

<u>Optimization</u>

- Power generation, transmission, and storage
- Reduce/Reallocate area, volume, and/or mass
- Anti-jamming
- Data Fusion
- Electrical and chemical propulsion
- Ancillary services (Communications, Navigation, Telemetry & Control Data, Experiment Data, etc.)
- On-orbit triple point conversion management of H_2O (i.e., ice, water, steam, and gases) to serve as propellants

<u>Bit Gathering/Processing/Transfer</u>

- Constellation Systems
- Fractionated Systems
- Multi-Use/Customer Platforms
- Integrated Platforms
- Stand-alone Spacecraft

<u>Human and/or Robotic Facilities</u>

- R&D Facilities

- Manufacturing Facilities
- Intermodal Facilities
- Processing Facilities (fuel, ores, etc.)
- Asteroidal Mining Facilities (water, ores, etc.)
- Hospitality Facilities (tourist)
- Habitation Facilities

In the near-term the emerging market is servicing ISS co-orbiting and other LEO systems. In the mid-term the emerging market will be degraded systems, augment requirements, and new systems designed to take advantage of the new utility resources. In the long-term immortal systems infrastructure will emerge as a driving market.

Retire Cost, Schedule, and Technical Risk for Space-to-Earth Facing Applications

- Other Electrical Utilities (existing & new)
  - Is less than 10 cents/kwh generation cost delivered to the grid possible?
  - Environmentally benign
  - Scalable to meet world demand
  - Accessible near where it is needed
  - Limited security issues
- Military Logistics

➔Cost per kWh is fungible provided that the required power is available where it is needed, when it is needed, with no exceptions

- Emergency Response Logistics
  - Readily deployable, reasonable to operate, relatively low cost
- Remote Infrastructure Alternative
  - Where Space Solar Power (SSP) is a cost-effective alternative to other available options
- Transportation Vehicles
  - Where SSP is a cost-effective mission-appropriate option
- Kinetic storage, water desalination, synthetic fuel production
  - Very low cost surplus power

Market Demand (a key consideration for commercialization of new technology)

- Is there a current market demand now or does it need to be created (and if so, how)?
- How much would potential customers buy now if wireless power were available?
- How much new demand would there be and where?
- How much supply could be made available?
- What pricing would be acceptable for each application?

Competition (who else supplies the product or service or is trying to?)

- If there is none, can you afford to make the market or do you need competition?
- International cooperation, collaboration, and competition inherently mixed environment
- What are the other alternative products or services that could become the competition?

The baseload power market is driven by the delivered cost per kWh to the grid. All other categories of power demand require a trade-off of cost to some extent to accommodate one or more other objectives. There are evolving opportunities to leverage investment from multiple United States government agencies.

Lunar Applications

- Electrical Relay Infrastructure (new)
- Exploration Vehicle Support
- Emergency Response Logistics
- Remote Infrastructure Alternative
- Transportation Vehicles
- Scouting, prospecting, mining, storing, and processing lunar materials
- Lunar surface system night survival
- Lunar operations in permanently shadowed craters

Bit Gathering/Processing/Transfer

- Ancillary Utilities (Communications, Navigation, Command & Telemetry, Payload Data, etc.)

Human and/or Robotic Facilities

- R&D Facilities
- Manufacturing Facilities
- Intermodal Facilities
- Processing Facilities (fuel, ores, etc.)
- Luna Mining Facilities (water, ores, etc.)
- Hospitality Facilities (tourist)
- Habitation Facilities

A key consideration is that all services that can be provided are mission-enhancing if not mission-enabling.

Supplier/Resources:

Logistics
- Earth Launch Systems
- Transfer Systems
- Luna Launch Systems

Low Mass Power Generation
- Photovoltaic
- Solar Concentrator
- Solar Dynamic

Radiant Energy Beaming
- Microwave
- Millimeter Wave
- Frequency Agnostic
- Laser

Other Technologies

- Robotic Assembly Assets
- Control & Damping of Large Structures
- Piece Part Manufacturing in Space
- High temperature tolerant electronics
- Radiation tolerant electronics
- Modular structures
- Network Control Architectures

Trading the state-of-the-art vs. Satisfactory & Sufficient vs. optimal is both a systems engineering and an economics challenge. Robotics and advanced automation are essential to meeting both challenges.

Transportation**:**

- Earth to LEO
- LEO to Earth
- LEO to LEO/MEO/HEO
- LEO to GEO
- LEO to Lunar Orbit
- LEO to Near-Earth Object (NEO)
- GEO to GEO
- GEO to LEO
- GEO to Lunar Orbit
- GEO to NEO
- Lunar Orbit to Luna
- Lunar Orbit to Lunar Orbit
- Lunar Orbit to GEO
- Lunar Orbit to LEO
- Lunar Orbit to NEO
- Lunar surface to Lunar Orbit
- Lunar surface transport
- NEO to NEO
- NEO to Lunar Orbit
- NEO to GEO
- NEO to LEO

The key consideration is how to foster the markets – the government(s) role as a modern day instance of the National Advisory Council on Aeronautics (NACA) or perhaps and/or an international equivalent as well as first customers (e.g., the United States airmail analogy).

Investment/R&D**:**

- Low cost launch
- Low cost transfers
- Low cost mass production
- High efficiency solar power generation
- Control and Damping of large structures
- Demonstration of Power Beaming
- High Temperature Solar Cells
- Luna/Lunar manufacturing

Value Proposition (why a consumer should buy this product or service?).

- Freedom from distance limitations of wires
- Eliminate penetrations through pressure shell
- Separation of micro-g experiments from vibration sources
- Continuous power available when solar is not available
- Eliminates/reduces need for batteries and related life and cost issues
- Reduce propellant mass needed to move energy storage system mass
- Eliminates military convoys through dangerous areas to transport fuel

Investor expectations (will not invest unless questions are answered and concerns are addressed)

- A great business plan exists that addresses key investment viability questions
- Demonstrable progress can be made quickly, both on technology and market penetration
- Early sources of revenue are available with an acceptable level of initial investment
- Preference to fund for growth after initial revenues are being produced
- Returns of a sufficient magnitude are possible
- Returns are likely within the investment horizon
- All foreseeable risks, including business risks, have been considered and strategies planned
- Risks are commensurate with expected gains

The orchestration that allows for matching between tranches of investment, staging of effort, and perceived and actual cost/schedule/technical risk and returns is critical to success.

Infrastructure

- Transportation System
- Network of Space Solar Power Satellites
- Ground Station "Rectennas" (rectifying antennas)
- Maintenance Capability
- Robotics, advanced automation, and human involvement needed for repairs, with the precise mix to be traded
- Asteroid Manufacturing
- Lunar Prospecting and Scouting
- Lunar Mining
- Lunar Manufacturing
- Lunar Habitation
- Lunar Surface Transportation

The development of infrastructure elements, appropriate linkages, and operational procedures must be driven by an understanding of the customer requirements and economics of satisfying them. Ideally, these understanding are reached and action is taken before a lack of resources creates a critical problem.

<u>Regulation</u>**:**

- Spectrum regulation
- Inspection of System for Compliance with Outer Space Treaty
- Space Traffic Control
- International Indemnification
- Debris Management and Mitigation
- Zoning on Earth Rectennas
- WHO compliance for Health and Safety

Creating a regulatory framework that is informed and driven by the confluence of interests necessary to grow the market in a rational manner is a fundamental statecraft challenge which we must rise to.

A strawman milestone chart is then derived for creation of the Lunar Power & Light (LP&L) company that indicates the venues of interest, application scaling, and a relative timeline, as well as related activities/actions as shown in Figure 2 – Energy TD^3 Milestones.

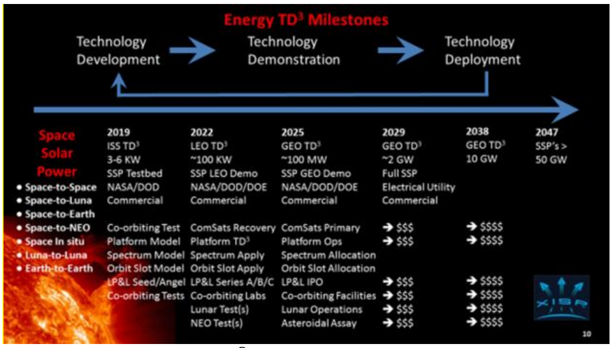

Figure 2 – Energy TD^3 Milestones

The process of developing a solution space typically draws out a number of challenge questions that have to be resolved in order for a mission to be realized. In this case, the Energy challenge questions include:

<u>Sectors</u> ➔ Orchestration is essential in a cooperative, collaborative, and competitive market.

<u>Products/Services</u> ➔ Cislunar Electrical Utility demand will scale with demonstrated supply.

<u>Customers</u> ➔ As soon as energy is available it will be used - Are customers really ready?

<u>Supplier/Resources</u>

➔ Establish standards, make economic sense and scale - reality check!?

➔ Robotics, advanced automation, and human involvement needed, with the precise mix to be traded

➔ System trades require iterative and recursive Technology Development, Demonstration, and Deployment (TD^3)

<u>Transportation</u> ➔ Match to mission requirements, be sustainable, and be affordable to use.

<u>Investment/R&D</u> ➔ Each increment of investment needs to lead to actual customer use. Each step must pave the way for the next step, and be a useful intermediate goal in its own right.

<u>Infrastructure</u> ➔ Elements, linkages, and operational procedures need definition & buy-in.

<u>Regulation</u> ➔ Consistent long-term government commitment to foster the market and help mitigate perceived as well as actual cost, schedule, and technical risk.

Based on this qualitative assessment it is asserted that a path linking near-term opportunities for SSPB with farther-term opportunities can be developed.

What this means for ISS is that taking an analogous approach, building on a combination of the existing XISP-Inc Mission development efforts (considered both individually, and synergistically with each other) and new opportunities that emerge through the research process significant optimization opportunities exist.

<u>II. ARCHITECTING AN EXTENSIBLE APPROACH AND FRAMEWORK</u>

The next step in architecting an extensible approach and framework is a core team creation of three extensible outlines to identify, articulate, and codify the solution space associated with LEO commercialization, using three different approaches:

A top-down approach based on mission requirements "pull," which reverse engineers the TD^3 mission commercial playout, which in turn meets postulated customer requirements for a quantifiable mix of end products, services, utilities, and supporting infrastructure.

A bottom-up approach based on technology development "push," which builds an iterative and recursive pipeline of TD^3 missions that result in commercial end product for each increment of resources invested.

A middle-out approach based on maximizing the utilization of all existing, in process, and contemplated infrastructure that can be leveraged to support LEO commercialization.

In conjunction with an open source "tough-room" of consultants (invited participants from all sectors), the core team will create an overlay of the three different annotated approach outlines defining the postulated solution space for fostering LEO commercialization.

This network of possibilities will then be untangled and organized into sets of connections that can be viewed as a logical progression of actions, or “threads,” to be considered for execution. The core team, with the assistance of the consultants as needed, will build, model, and document the qualitative and quantitative case for each of these “threads” in successive challenge presentations/briefs addressing each review item discrepancy raised by the collective tough-room critique. This process will result in an enduring extensible product: a roadmap consisting of interleaved threads of actions to establish a self-sustaining commercial Cislunar Marketplace.

III. ADDITIONAL CONSIDERATIONS

All five of the TD^3 mission examples defined above have previously been found to be relevant to NASA’s future needs by NASA Headquarters HEOMD and multiple NASA center reviews including NASA JSC Code OZ representatives.

The goal of this ongoing effort is to draw out and define at least at a conceptual level TD^3 missions addressing the evolution of every distributed system and functional element of the ISS, all of which are germane at some level to the commercialization of human spaceflight in LEO and NASA’s future needs.

Several of the TD^3 mission examples offered have been recommended to go forward as commercial missions by NASA Headquarters HEOMD and NASA JSC Code OZ representatives based on the contention that they could be of commercial significance to human space flight in LEO and beyond.

The underlying mission development work draws on over 65 papers, presentations, and poster sessions on the TD^3 mission examples cited in this paper and related topics at multiple professional fora including ISS R&D conferences (1 through 6), AIAA Space 201X conferences, ISDC 2005-2019, IAC 2014, 2016, 2018 WiSEE 2013, 2015 & 2017.

The Power example provided as an attempt to not only articulate an understandable approach to TD^3 mission development but one that has actually being implemented within the context of an evolving public-private partnership with the advice and consent of NASA HEOMD. While the business case playout was identified for all five TD^3 mission examples provided, the development of the related business case concept was only provided for the SSPB mission. The ongoing work will provide the business case development for all TD^3 missions identified going forward.

IV. RELEVANCE

In the development of the work assertions have been made that the initial mission set being examined is only very marginally relevant to the commercialization of LEO or NASA's future needs. Given the above a reasonable logical test is test the veracity of the assertion of relevance one clause at a time . . .

The contention that use of low cost configurable spacecraft for Earth facing, Cislunar infrastructure, and beyond Earth orbit applications (represented by the Alpha CubeSat TD^3 mission) is only very marginally relevant to the commercialization of LEO or NASA's future needs is inconsistent with stated NASA HEOMD and SMD policy and programmatic plans, actual current and planned ISS utilization, and the growing commercial market for smallsat applications/constellations.

The contention that a Space-to-Space, Space-to-Alternate surface, and Surface-to-Surface Electrical Power and Ancillary Services utility for Cislunar space (i.e., from the Karman line at 100 km through to the surface of the Moon – represented by the SSPB TD^3 mission) is only very marginally relevant to the commercialization of LEO or NASA's future needs is inconsistent with the NASA HEOMD position on the SSPB TD^3 mission and involvement of a consortium of over 9 commercial companies, 17 independent consultants, 3 government agencies, 4 non-profit organizations, 6 universities, and 3 international space agencies in its mission development. Furthermore, the ability to provide power and ancillary services when and where needed is essential to virtually all aspects of human endeavor and enables all forms of space development/settlement. The SSPB mission will deliver significant commercial value in the form of power and bi-directional ancillary services to a growing number of customers interested in co-orbiting with the ISS and lay the foundation for a myriad of Cislunar applications.

The contention that the use of ISS as a TD^3 transportation node for low cost, readily deployable Earth, Cislunar, and beyond Earth orbit mission support is only very marginally relevant to the commercialization of LEO or NASA's future needs is inconsistent with current and anticipated commercial markets and NASA mission plans.

The contention that use of ISS as a TD^3 platform for Communications and Navigation Utilities and interface kits for Earth-facing, on-orbit, and space facing applications is only very marginally relevant to the commercialization of LEO or NASA's future needs is inconsistent with current and anticipated commercial markets and NASA mission plans.

The contention that the use of the ISS as TD^3 testbed for near–real-time state models, mutable locus of control systems, and virtual operations centers to facilitate crewed and tele-operated/shared control and autonomous in situ operations, reducing crew time required for experiments and increasing ISS productivity is only very marginally relevant to the commercialization of LEO or NASA's future needs is inconsistent with current and anticipated commercial markets and NASA mission plans.

Given that the XISP-Inc commercial TD^3 mission set (the source of the examples cited) has been developed on a minimal budget the contention that a concerted effort of 25 highly qualified experts with a wide range of space experience and a substantive budget could not apply the TD^3 mission development process outlined above in a manner very relevant to the commercialization of LEO and NASA's future needs seems logically inconsistent.

V. CONCLUSION

This paper has laid out a framework for an iterative and recursive process to examine every ISS system and element for opportunities for stand-alone and integrated evolution to support multiple applications consistent with the context of the defined TD^3 missions.

The commercialization concepts, business plans, and viability of habitable platforms in Low Earth Orbit (LEO) are critically dependent on an evolvable infrastructure that will provide the necessary utilities and ancillary services to accommodate addressable markets for the International Space Station (ISS) directly as well as for free-flying spacecraft and their aggregations. Markets for the above are and will be driven by explorations, operations, and applications that will be run by a combination of government, international partner, non-profit, and commercial entities. Orchestrated extraordinary innovative public/private partnerships that leverage existing and evolving space and ground infrastructure, commercial investments, academic and non-profit resources, and intergovernmental agreements to blaze a roadmap to the commercialization of LEO are essential for the cost-effective commercialization of LEO and beyond.

The author postulates that these markets are best developed by the support of the evolution of ISS as a Technology Development, Demonstration, and Deployment (TD3) infrastructure to support the commercialization of LEO and beyond.

By facilitating the ISS' ability to serve as LEO commercialization infrastructure that can foster the definition, execution, and accomplishment of a pipeline of TD^3 missions, the synergistic effects can be maximized along with the other modes (e.g., science laboratory, operations center, transportation node, etc.) of utilization.

This provides a foundation for progress reporting on the research, identifying, and articulating the qualitative and quantitative narratives for TD3 missions detailing how to stimulate the private demand for commercial LEO services in order to sustain the long-term LEO addressable markets with primarily non-NASA commercial revenue. For each TD^3 mission, the combination of "technology development push," "mission requirements pull," and "commercial applications/infrastructure playout" will be researched and evaluated.

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21. 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
22. 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
23. 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
24. Barnhard, Gary Pearce; Dahlstrom, Eric; Chew, Ethan – "Halfway to Anywhere" - AIAA 21st Improving Space Operations Support Workshop, Pasadena, CA – Presentation May 6, 2015
25. Barnhard, Gary Pearce – "Interoperable Network Communications Architecture" - AIAA 21st Improving Space Operations Support Workshop, Pasadena, CA – Presentation May 6, 2015
26. 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
27. 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
28. 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

29. Barnhard, Gary Pearce, “Unbundling Space Solar Power Systems” - 4th Annual ISS R&D Boston, MA – Poster Session July 2015
30. 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
31. 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
32. Barnhard, Gary Pearce – “Interoperable Network Communications Architecture” & “Alpha Cubesat” - International Space Development Conference (ISDC) 2016, San Juan, PR – Presentation
33. Barnhard, Gary Pearce; “Mission Operations Control Applications (MOCA) to Advanced Vision and Task Area Recognition (AVaTAR)" – Presentation to the NASA Future In Space Operations (FISO) Colloquia June 22, 2016
34. 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
35. 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
36. 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
37. 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
38. 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
39. 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
40. 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
41. 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
42. 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
43. 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
44. 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.
45. 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.
46. 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.

47. 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.
48. 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
49. 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
50. 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
51. 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
52. 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
53. 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
54. 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
55. 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
56. Barnhard, Gary Pearce, "Space Solar Power & ancillary services Beaming as enabling infrastructure", Space Solar Power Symposium ISDC 2019, Washington, DC – Presentation June 5, 2019
57. Barnhard, Gary Pearce, "Surface-to-Surface customers", Space Solar Power Symposium ISDC 2019, Washington, DC – Presentation June 5, 2019
58. Barnhard, Gary Pearce, "Space Solar Power & Ancillary Services Beaming: Creating Enabling Infrastructure as a Commercial Enterprise", NASA ARC Commercial Space Telecon/Colloquia – Presentation July 10, 2019
59. 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
60. 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
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