ISS: A Partner in Enabling Space Exploration Through Reduction of Risk

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"The best way to predict the future is to create it."
Managing for Results by Peter F. Drucker

Abstract

Many management and engineering solutions contribute to the strength of a program. Management integration in cost, schedule, and technical risk areas can have a significant effect on program success. An assessment of cases from several spaceflight programs and the ISS results in recommendations that can lead to future success. The ISS is currently the largest space exploration program in the world. It involves several major aerospace companies and international space agencies as partners. The ISS Program is of importance and relevance to the Space Exploration Vision, particularly in the utilization of the ISS as a test bed for new technologies and techniques in support of CEV and Lunar Mission hardware design and development.

I. INTRODUCTION

The International Space Station (ISS) has been, and will continue to be, instrumental to the exploration of space. During the course of the ISS Program, NASA has amassed critical insight in many areas crucial to space exploration and will further increase this knowledge as ISS progresses with assembly, operations and utilization. Knowledge has been gained in all areas, including management, integration, operations, assembly, maintenance, International Partner relationships, life sciences and engineering. NASA is at a critical juncture at this time, beginning implementation of the Exploration Program in parallel with ISS operations. Careful forward planning and strong commitment can maximize the potential benefits gained from the ISS Program and reduce risk to the Exploration Program, while also maximizing synergies between the two Programs for optimum resource usage. This requires that both programs work together now to develop a strategy for implementation.

This paper will address areas for future use of the International Space Station to raise technology levels and/or validate concepts, designs, or technologies. The ideas listed can be planned in such a way that they will be beneficial to both the Exploration and ISS Programs. It does not address previous lessons learned applicable to Exploration.

II. ISS as A Tested for Exploration Systems and Operations

ISS affords a unique opportunity to serve as an engineering test bed for hardware and operations critical to the exploration tasks. The ISS is a large, complex spacecraft operating continuously in space and maintained by the onboard crew. Similar to spacecraft that will support future missions beyond low-Earth orbit, ISS does not return to the ground for servicing, and provisioning of spares is severely constrained by transportation limits, especially upon Shuttle decommissioning.

The ISS can be viewed as an ideal platform to use for mitigation of risks that cannot be assessed correctly on the ground or are better reduced in space. The ISS is a viable, and in many instances the only, test bed available in the near term for increasing technology readiness levels and/or validating concepts and technologies for human space flight in space environments such as microgravity, thermal, radiation and contamination environments.

This presents NASA with a unique opportunity for technical and acquisition collaboration across two large NASA Programs, Space Exploration and the International Space Station.

A. Areas of Applicability

Based on experience, even if the Space Exploration Program successfully implements all of the best practices developed by NASA and industry to date, it cannot eliminate the risk inherent in its program. Utilization of the ISS can help to mitigate these risks from an engineering and operations standpoint, as well as maximize the United States and International Partners/Participants' investment in the human space program. The ideas listed below have the potential to benefit both Exploration and ISS. However, other exploration-specific concepts could be addressed and planned into ISS operations and should not be ignored if they have a higher priority than items listed.

In some cases, Exploration has approved Intramural Proposals and/or Extramural Proposals that are pre-cursors to flight demonstrations on ISS. As these projects show promise, and as Exploration determines the priorities of the projects, ISS planning to integrate into flights and operations should begin.

Areas identified as being particularly relevant for use of ISS as an exploration test-bed include:

- Space Natural Environments and Effects – validation of integrated space environment models such as radiation, meteoroids, and electrical charging (plasma), with the extrapolation of the orbital environment and mitigation methods to the exploration environments. Validation of concepts/designs for improved radiation, micrometeoroid debris, and noise protection. These factors should not be underestimated as there were major oversights in the natural environment which resulted in inadequate features of the ISS design and which required subsequent augmentation.
- Robotics – Flight demonstrations of new robotic designs/concepts or operational scenarios for assembly or maintenance tasks.
- Sensors and Manipulators - Integrated Suite of imaging sensors and manipulators for in-space system inspection or operation. The capability to perform a wide variety of local inspection and control operations can be important to the long-term, robust operation of diverse systems in deep space and planetary venues.
- Advanced Life Support Systems – increasing technology readiness and/or validating designs for closed loop life support systems such as oxygen generation and waste (water) recycling.
- Long-duration Crew Health and Performance – provide valuable data on the long-term effects on the human body and psychology.
- Crew health care and exercise – Validate concepts for advanced crew health care and exercise concepts.
- Human Interfaces - Applicability of rich multi-modal human interface systems (visual, haptic, speech, etc.) to problems such as: (i) human-robotic on-orbit assembly of structures, (ii) distributed anomaly response systems for advanced life support or vehicle emergencies, (iii) augmented and synthetic reality vision, etc.
- Assembly Operations - Efficiency, speed and preciseness of in-space assembly systems at a large-scale (e.g., cranes), mid-scale (e.g., anthropomorphic robots), or small-scale (dexterous and/or micro manipulators), reliable in-space self deploying systems, and self-assembling systems for applications in Earth-orbit, the Moon, and beyond, including intelligent and robust docking mechanisms, as well as robust, autonomous rendezvous and docking technologies and test beds.
- Advanced Power Systems; Fuel Cells; Batteries - Flight demonstrations to raise technology readiness or prove out design concepts.
- CEV rendezvous and docking – flight demonstration of CEV rendezvous and docking capability and design.
- Operational Concepts – ISS could be used to investigate possible scenarios that would exist in Exploration, for instance a "day without communication between ground and crew".
- Synergy with Future Spares – To account for the decommissioning of the Shuttle, the ISS Program is in the process of updating its sparing and maintenance concepts. This will require more in-flight maintenance and procurement of additional spares. Some of these spares can incorporate new technologies/designs that will benefit Exploration and ISS simultaneously.

III. Conclusion

We view the ISS as an ideal platform to approach the mitigation of risks that are either very difficult or cannot be mitigated on the ground. Capturing the potential lessons learned from using the ISS as a testbed for new technology will make better equipment for long duration Space Exploration flights.

The ISS is a viable, and in many instances the only, test bed for the concepts, which need to be validated in space microgravity, thermal, radiation and contamination environments, to advance technology readiness.

It is well known that upmass, downmass, and crew time are severely limited in the ISS Program. This issue is being addressed with emphasis on the need to support Exploration objectives. Priorities and strategies will need to be addressed and developed ahead of time to ensure maximum use of these resources to NASA. It is imperative that the two programs form and alliance and develop a strategy for more effective implementation.

NASA is embarking on a new and exciting chapter in space exploration. The new vision for space exploration calls for a sustained, achievable, and affordable human and robotic program to explore the moon, Mars and beyond. The ISS plays a critical role in paving the way for human space exploration beyond low Earth orbit. The President has given NASA the goal to complete assembly of the ISS by the end of this decade and to re-focus U.S. research and use of the ISS on supporting space exploration goals, with emphasis on understanding how the space environment affects astronaut health and developing countermeasures and spacecraft systems, such as those for life support.

Environment is a critical success factor and even if the Space Exploration Program successfully inherits and implements all the best practices, developed by NASA and industry to date; it can not eliminate the risk inherent to any new program. However, extensive utilization of the ISS can help to mitigate this risk from the engineering standpoint. This presents us with a unique opportunity for technical and acquisition collaboration across the two largest NASA Programs, Space Exploration built on the foundation and experience of the International Space Station.

The Space Station serves a wide variety of purposes. It is a microgravity and life sciences laboratory, a test bed for new technologies in areas like life support and robotics, and a platform for astronomical and Earth observations. It is the cornerstone of the vision for space exploration. Assembling and operating the International Space Station has been producing advances in our knowledge about how we can live and work in space for long, continuous periods of time, and even the loss of *Columbia* has had effects on logistics support that has resulted in new knowledge and experience about how to support extended missions at planetary distances. The knowledge we are gaining is critical for our future journeys.

IV. Acknowledgements

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V. ADDENDUM A

Addendum A is a subset of already existing requirements documented in reference (3) that can be verified on the ISS.

* CTS0050H: The CTS shall provide the capability to monitor, command, and control the system segments and elements.

Rationale: Mission success and the safety of the flight crew, ground personnel and the general public will be dependent on the ability of the CTS to monitor, command and control the system, segments, and mission elements. A critical capability required for public safety is the ability of the Range Safety System to track launch vehicle trajectory and performance and issue flight termination commands if required. Another example is the ability to detect and annunciate mission and safety critical conditions, isolate the conditions, and provide for recovery of mission and safety critical functions.

* CTS0075H: The CTS shall provide automated control linked to the mission phase and function.

Rationale: A high degree of automation is desired for the CTS to minimize the number of routine tasks required of the crew and mission control personnel. The cost of automation must be balanced against development cost, schedule, and technical risk. This requirement is a broadly defined parent for lower-level requirements that will specify levels of automation.

* CTS0300H: The CTS shall provide autonomous operations linked to the mission phase and function with an objective of autonomous operations throughout the mission.

Rationale: A high degree of CTS autonomy is desired for the CTS. Autonomy is required for functions for which there is not reasonable time for human response. A defined methodology should be applied to each mission phase and vehicle function to determine how much automation is needed, and to assess where it is cost effective. This requirement serves as a broadly defined parent for lower level requirements that will specify the level of autonomy.

* CTS0320H: The CTS shall provide manual intervention of automated functions critical to mission success and crew safety.

Rationale: Manual intervention of automated control can be executed by ground control personnel or the crew. Human intervention capability is required to ensure that automated functions do not perform actions that are inappropriate in a particular failure scenario. For example, previous system or sensor failures may make an automated response undesirable. Crew intervention requirements are covered in NPR 8705.2.

* CTS0125H: The CTS shall provide for TBD contingency EVA during operations in Earth orbit (TBD-33).

Rationale: Contingency EVA capability was specifically identified by the Operations Advisory Group (OAG) as a high priority capability. TBD Closure: Specific contingency tasks cannot be identified until the CTS elements have been designed. Therefore, this requirement will remain TBD, pending further study.

* CTS0190H: The CTS shall detect and annunciate conditions which could result in loss of human life, loss of vehicle, loss of mission, or significantly impact mission capability.

Rationale: This requirement captures functionality, such as Integrated Health Management, for the detection of system failures. For situational awareness, the crew and ground control must be aware of significant changes in vehicle status, even if automated systems respond to the condition. This requirement intentionally does not specify all failures - which is not practical. Also, it is left to the program to interpret "significantly impact mission capability" in the lower level requirements. This requirement serves as a parent to flight element health status monitoring requirements.

* CTS0200H: The CTS shall provide autonomous isolation and recovery, with an objective of automated isolation and recovery, from conditions which could result in loss of human life or loss of vehicle.

Rationale: This requirement captures functionality, such as Integrated Health Management and redundancy management, for the detection and mitigation of system failures. Reliance on communication with mission control to avoid loss of vehicle or loss of life is not acceptable. Automated recovery should be used when practical, and for all cases where the time required for human response will not prevent the loss.

* CTS0240H: The CTS shall provide communication in accordance with the TBD Constellation Systems IRD (TBD-66).

Rationale: The complexity of possible architectures and the serial acquisition of Exploration elements dictate a standard communications interface between all elements of the Exploration System of Systems. "Communication" includes command, data, voice and video. Constellation Systems must define the standard communications system in an IRD to include bandwidth, rates, security, etc. The CEV and the CEVLS are the first CTS elements that will comply with this interface document.

* CTS0250H: The CTS interface with the Ground Support System shall comply with the requirements of the TBD CTS / Ground Support System IRD (TBD-67).

Rationale: The CTS will interface with Ground Support Systems such as Mission Control and recovery / rescue forces. The CEV and the CEVLS are the first CTS elements that will comply with this interface document.

* CTS0260H: The CTS interface with the In-Space Support System shall comply with the requirements of the TBD CTS / In-Space Support System IRD (TBD-68).

Rationale: The CTS will interface with the In-Space support System such as communications satellite systems and navigation satellite systems. The CEV is the first CTS element that will comply with this interface document.

* CEV0230H: The CEV shall detect and annunciate conditions that could result in loss of human life, loss of vehicle, loss of mission, or significantly impact mission capability.

Rationale: This requirement captures functionality, such as Integrated Health Management, for the detection of system failures. For situational awareness, the crew and ground control must be aware of significant changes in vehicle status, even if automated systems respond to the condition.

* CEV0047H: The CEV shall capture and archive mission and safety critical performance data.

Rationale: The ability to capture mission and safety critical performance data, and archive it in a retrievable format is necessary to support real-time anomaly resolution and post-mission data analysis.

* CEV0300H: The CEV shall communicate in accordance with the TBD CTS IRD (TBD-66).

Rationale: The complexity of possible architectures and the serial acquisition of Exploration elements dictate a standard communications interface between all elements of the Exploration System of Systems. Communications includes command, data, voice and video. Constellation Systems must define the standard communications system in an IRD to include bandwidth, rates, security, etc. The CEV and CEVLS are the first CTS elements that will comply with this interface document.

VI. ADDENDUM B

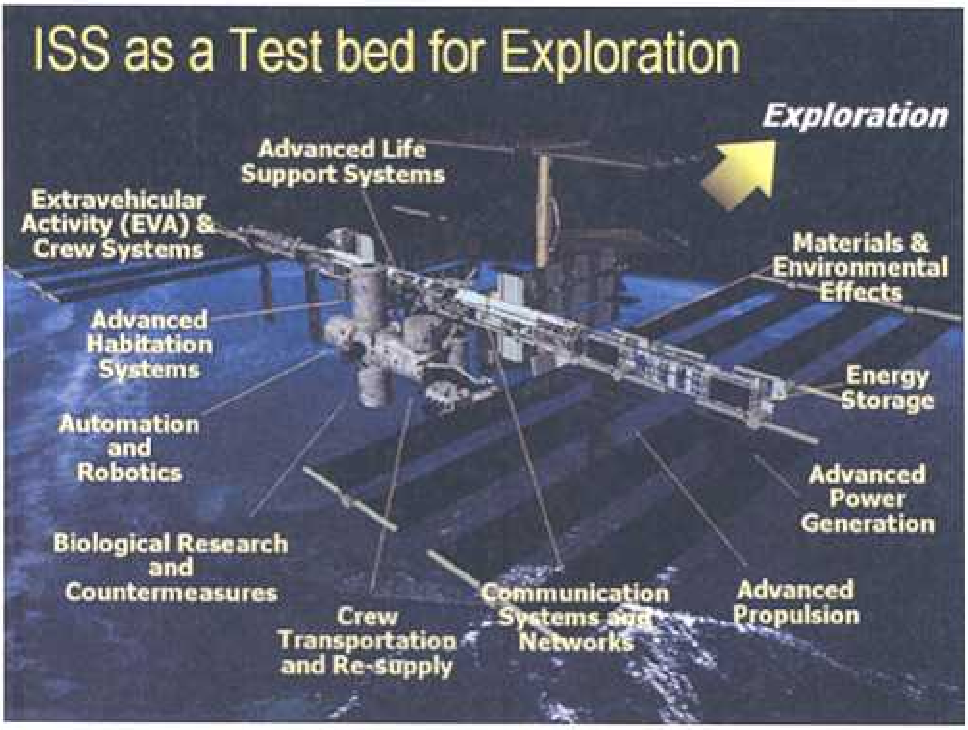


Figure B-1. Utilities and Candidate technologies for validation on the ISS

The ISS as testbed provides many important utilities for future payloads as defined in reference (10):

- Large test area for payloads
  - Electrical power.
- The ISS contains 8 independent power channels with primary power capability of 11 kW each (capability varies with operating conditions, age, beta angle, etc.)
- Each DDCUs can provide secondary power (120 Vdc) at 6.25 kW and two DDCUs can be operated in parallel for a total power capability of 12.5 kW
  - Recirculating coolant at ~ 35 °F
  - Cables to collect data from test article and to provide computer control
- Data can be transmitted to ground and / or stored on orbit, as needed
- 1553 bus can provide interface with computers on ISS, if needed
- On-orbit crew can interact via laptops, if needed
  - Two-way communication with ground
  - On-orbit crew extra vehicular activity support,
- Cable junction boxes and fluid quick disconnect couplings exist at truss joints

VII. ADDENDUM C CANDIDATE TECHNOLOGIES (Reference 6)

Variable Specific Impulse Magnetoplasma Rocket (VASIMR), that is currently under development at JSC. VASIMR is an electrodeless, electrothermal, RF-heated plasma propulsion device capable of continuous thrust/ Isp modulation at constant power. (Reference 5)

- Thrust produced by VASIMR can be used for ISS drag compensation VASMIR can serve as plasma contactor for the ISS.
- VASIMR can serve as plasma contactor for the ISS.

VII. POTENTIAL ISS LOCATION

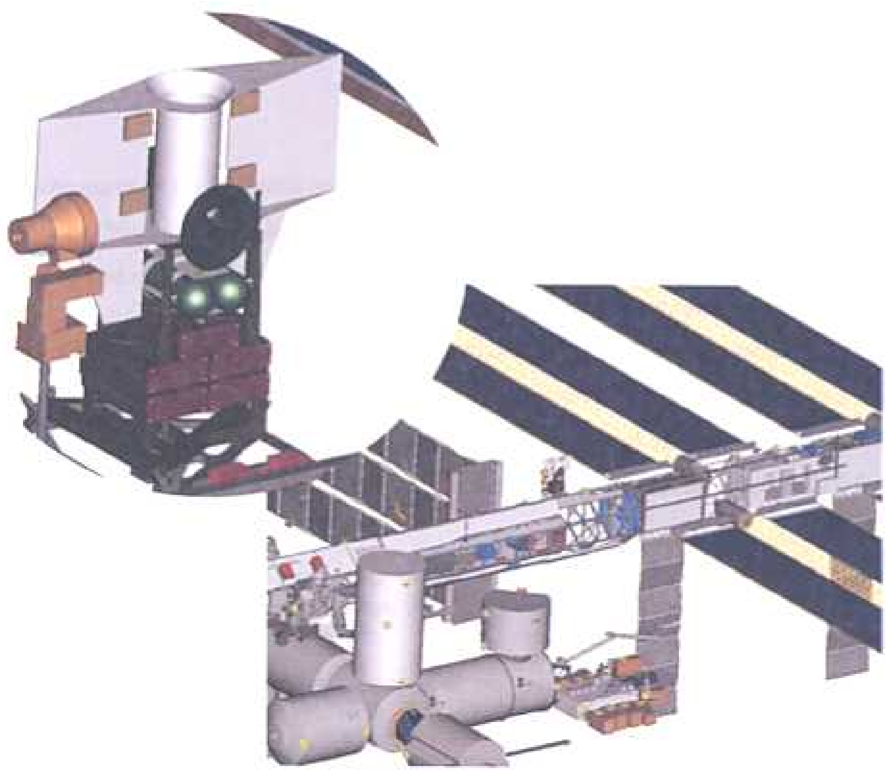
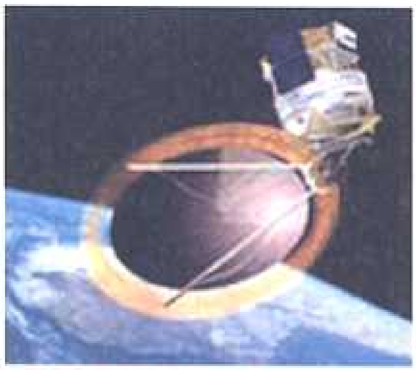


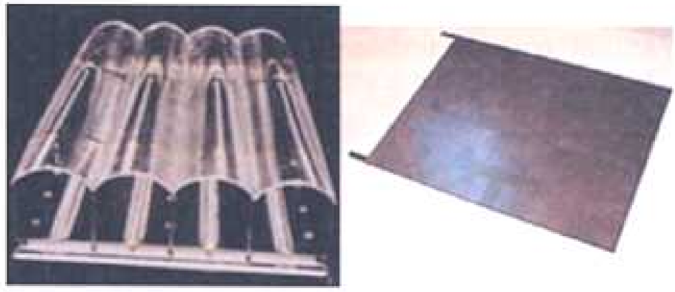
Figure A-2. Attachment at external payload site on P3 (or S3) truss segment shown

A. Advanced Solar Array Technology (Reference 6)

- Test articles that utilize solar energy can be mounted on outboard truss to take advantage of ISS alpha pointing
- Testing on ISS will help advance technical maturity of concentrating and non-concentrating photovoltaic arrays
- ISS can store electric power generated by the test article during isolation periods and provide electric power to sustain the test article during eclipse periods



Deployable Solar Concentrator



Lightweight PV Arrays

Figure B-3

B. Thermal Power Conversion Technologies (Reference 6)

- ISS can be utilized to test and validate thermal power conversion technologies in space environments
- The test articles may be mounted outboard of the alpha gimbals to take advantage of ISS alpha pointing
- Early External Active Thermal Control System hardware on P6 Long Spacer may be re-activated to provide recirculating cooling fluid for the test article, if needed
- Batteries on PV modules may be utilized to smooth out the electric power output of the test article
- Data from the test article can be collected via 1553 bus, stored on orbit and transmitted to ground
- On-orbit computers can provide computer control for test article via 1553 bus
- Crew on-orbit can provide EVA support, if needed

Li-Ion battery technology:

- Highly efficient and long life energy storage systems are essential to enable Space Exploration Vision NASA and Boeing NASA Systems have been actively pursuing the application of Li-Ion batteries for ISS and other space application for several years
- A flight experiment using Li-Ion batteries on ISS would provide the applicable data and technology maturity needed for manned space applications.

Figure A-4. LI-Ion battery cells, credit - NASA GRC

C. **Advanced ECLS systems (Reference 7)**

- ISS can be used to test advanced in space based ECLS systems
  - Ground based technologies can be tested more efficiently on the ground
    - Might be some exceptions for small proof of concept experiments
- Most notable candidates
  - Sabatier - Carbon Dioxide Reduction
    - Further closes the water loop
    - Still dumps some CO_2/CH_4 overboard
  - High Pressure Oxygen Generator
    - Allows for in-situ creation and maintenance of high pressure oxygen resources
    - Water is an efficient way to transport oxygen verses tankage (cryo or high pressure)
  - Trace Contaminant Monitoring
    - Monitoring of specific list of trace contaminants for in-situ analysis is required for any long term closed environment
  - Static air/water separators
    - Current dynamic separators have limited life
  - (High Pressure) Nitrogen Generator
    - Allows for in-situ creation and maintenance of (high pressure) nitrogen resources
    - Some form of N_xO_x (Ammonia is also a potential candidate) is an efficient method to transport nitrogen verses tankage (cryo or high pressure)
  - Waste (Trash) Oxidizer
    - Allows to even further close all loops via recovery of H_2, O_2, and N_2 from solid wastes (human solid wastes, food wastes, etc)
  - Biologically based Water Processor
    - Less logistical requirements
  - Bosch - Carbon Dioxide Reduction
    - Produces carbon; no hydrogen is lost
    - Large in size and power requirements

D. **On-orbit repair depot**

1. Demonstrate repair processes in unique micro-g environment.
2. Station is viable and only environment satisfying these requirements, it has direct benefit to ISS by reducing ISS logistics support requirements and supports 2+ spirals of exploration

E. **Virtual Control Center**

- Demonstrate an affordable and flexible ground support approach for monitoring and control of in-flight operations:
  - On demand utilization of skills
  - Effective utilization of critical skills
  - Provide reduced operations costs and efficient access to existing data streams and retrieval of ISS data

F. **Technical Approach:**

- Situational awareness for ground decision makers by making data available anywhere/anytime
- Integration of existing flight data capabilities at existing workstations/devices (pagers, blackberry's, etc.) outside of the MCC/MER

G. Crew Information Interfaces for the ISS, Space and Planetary Environments. Enhanced In-Flight Operations and Maintenance Data

Designing smart interfaces between the EMU and pertinent information databases on board the vehicle and on the ground is imperative for improving mission performance and safety. Current EVA communications interfaces are limited to voice communications, one-way telemetry of astronaut life support, physiological data, and one-way video via the EMU helmet mounted camera. On-orbit ISS operations suffer from a dearth of communications infrastructure components, which have the potential to dramatically improve the flexibility, robustness, and safety of future EVA operations on the ISS and for the Space Exploration.

With one-way line-of-sight light-travel-time delays of 4.5 to 21 minutes between Earth and Mars, EVA operations on the Martian surface are likely to be autonomous or semiautonomous and based on the skills-based training rather than scripted tasks. (23)

The improved information interfaces will increase crew and vehicle safety and reduce costs associated with operations training. These objectives will be achieved through:

- Enabling a multi-modal optimization framework across mission architectures by applying advanced human-machine interface technologies to decision making models for time-critical actions.

- Designing intelligent data communication interfaces between the crew and imagery, operational and other pertinent information databases on board the vehicle and on the ground.

- Including redundancy, advanced error correction protocols and decentralized design architecture, allowing entire components and software/hardware strings to fail without degrading the performance of the entire system.

- Providing the ISS as a test-bed to integrate and evaluate other projects throughout their TRL life cycle to ensure a data rich environment for the system-of-systems architecture and enabling capability for technology infusion and future architectural evaluation.

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