INTEGRATION TESTING OF SPACE FLIGHT SYSTEMS

Stephanie Sowards
Timothy Honeycutt
Integrated Test & Verification
Ground Operations Project, Constellation Program
NASA, Kennedy Space Center

ABSTRACT

This paper discusses the benefits of conducting multi-system integration testing of space flight elements in lieu of merely shipping and shooting to the launch site and launching. "Ship and shoot" is a philosophy that proposes to transport flight elements directly from the factory to the launch site and begin the mission without further testing. Integration testing, relevant to validation testing in this context, is a risk mitigation effort that builds upon the individual element and system levels of qualification and acceptance tests, greatly improving the confidence of operations in space. The International Space Station Program (ISSP) experience is the focus of most discussions from a historical perspective, while proposed integration testing of the Constellation Program is also discussed. The latter will include Multi-Element Integration Testing (MEIT) and Flight Element Integration Testing (FEIT).

KEYWORDS

Multi-Element Integration Testing (MEIT), Flight Element Integration Testing (FEIT), Interface Verification Testing (IVT), verification, validation, test, emulator, simulations, qualification, system, element.

HISTORY

Ship and shoot has always been a goal as seen by program managers from the Redstone Rocket Program in the mid 1950's through Mercury, Gemini, and the Apollo Programs, including the Saturn family, IB's and V's, to the current Space Shuttle Program. A companion goal of ship and shoot has been to utilize a set of factory checkout equipment at the launch site. There also have been program proponents to use the same test procedures at the launch site as those used at the factory. Each of these goals may seem feasible at the beginning and during the early phases of the program. However, the real world of delivering flight hardware and Ground Support Equipment (GSE) to the launch site has provided sufficient negative experience to hamper the achievement of these goals.

Another point that emphasizes the need for integration verification is revealed on the Shuttle Program. As of 2001, this Program no longer required the contractor to conduct integrated hazard analysis. They were only required to perform analysis at component and element levels, and not required to evaluate the Shuttle as a whole. Exclusively using a "bottoms-up" verification approach at the component level means that a "top-down" verification cannot be effectively supported, which is needed to determine risk trends and identify potentially harmful interactions between systems.

A prevalent experience has been that the flight hardware has been shipped to the launch site prior to being fully completed, tested and accepted. History says that this condition has been promoted by both the program and the contractor to meet program advertised ship dates as well as the contractor who has the ship date as a metric milestone in the contract. There is a host of factors that can drive failure of the mission including hardware arriving at the launch site late with "open work", hardware that has never seen its ground or flight interfaces, factory checkout only focusing on getting by to meet contractual milestones, launch site checkout focusing on hardware working with all interfaces, launch site checkout being the last chance to verify quality of hardware for flight, and launch site inspections discovering many discrepancies such as bent connector pins, loose fluid fittings, tools left in compartments, damaged wire bundles, and debris. These factors cause inherent safety risks as well as technical difficulties.

The ISSP baseline was originally intended to be ship and shoot. Factory level testing and element interface verifications at the subsystem-level, and interface analysis were all that was planned. In the spring of 1996, the testing evolution added the ISS Flight 2A Interface Verification Test (IVT), and various Program changes expanded requirements for Shuttle Avionics Integration Laboratory (SAIL), Cargo Element, and IVT.

Availability of elements at the launch site created a feasible opportunity to test multiple elements together, and it was decided that ISS elements would not be launched until extensive integration testing was performed prior to launch of these elements. The notion of verification on the ground was presented and accepted by the Program due to the criticality of the on-orbit functionality, including safety concerns for the crew. Multi Element Integration Test (MEIT)/Integrated Systems Test (IST) verified the operation of the flight element in an environment that was as flight-like as possible. Space Station element-to-element interface capability was verified as well as systems end-to-end operability with hardware and software. MEIT also verified limited on-orbit scenario system compatibility. The Mission Sequence Test (MST), also known as "end-to-end" integration testing, included a full-up configuration with the Mission Control Center, Tracking and Data Relay Satellite System (TDRSS) satellite communication, and the "station" operating on the ground. This allowed for a complete flight-like configuration that utilized critical communication links.

ISSP MEIT TEST CONFIGURATIONS

Three Multi-Element Integration Tests and one Integration Systems Test (IST) were conducted for the ISS. Within each MEIT, there were several ISS test configurations. At a high level MEIT1 consisted of US Lab, Z1 truss, P6 truss, and a Node1 emulator. MEIT2 consisted of S0 truss/Mobile Transporter/Mobile Base System, S1 truss, P1 truss, P3 truss, P4 truss, and a US Lab emulator. MEIT2 boasted the largest payload test in history, with over 3000 cables. MEIT3 included the Japanese Experiment Module, Node2, and the US Lab emulator, which morphed into the ISS Flight Emulator as it was augmented to represent multiple ISS elements throughout the program. Finally, the Node2 IST was comprised of Node2 and US Lab and Node1 emulators, as part of the ISS Flight Emulator.

ISSP MEIT MAJOR FINDS

During the multi-element integration tests conducted for ISS, significant problems that could only have been found in an integrated configuration with the multi-element flight hardware and software were identified and corrected. These problems would have seriously impacted Station assembly operations. Many other problems have also been found and corrected or had program workarounds prior to flight. Over 5000 verification requirements were accomplished.

Examples of major finds during ISS MEIT/IST testing are as follows.

- The Assembly Power Converter Unit (APCU) was redesigned after power losses due to breaker trips during the ISS P6 element activation on the ground before flight. The impact would have prevented the activation of P6 on-orbit, driving a shuttle re-flight of P6.
- During MEIT2, video lines were found to be swapped between United States On-Orbit Segment (USOS) Trailing Umbilical System (TUS) and the Canadian Mobile Base System (MBS). This would have operationally impacted manual routing of video signals from the Space Station Remote Manipulator System (SSRMS) to Robotics Work Station (RWS), thus requiring a time-consuming Extra Vehicular Activity (EVA) to swap these two harnesses.
- Multiplexer/De-Multiplexer (MDM) computer task overruns resulted in US Lab Command and Control (C&C) computer switchovers. This would have resulted in a loss of vehicle commanding and vehicle health visibility to the crew and ground.
- The initial US Lab element critical activation took 36 hours, and the requirement was less than two hours. The impact could have resulted in the loss of the US Lab element during on-orbit activation due to thermal loading timeline requirements.
- Mass property units were mismatched between the RWS and the US Lab C&C, which could have resulted in attitude errors, adding propellant usage.
- The Video Processing Unit design was changed after jittery orbiter video signals were found in the US Lab.
- External (EXT) MDM computer task overruns were discovered upon enabling planned on-orbit applications, impacting the start of the primary cooling system.

- A SSRMS/RWS software problem that would have prevented the first SSRMS walk-over attempt was corrected prior to flight.
- An electrical short was corrected on the Flight Support Equipment Grapple Fixture (FSEGF), preventing the SSRMS power-up; a minimal impact would have been an unscheduled EVA to identify and correct the problem, while a maximum impact would have been a SSRMS shuttle re-flight.
- It was discovered that redundant video synchronizations supplied from the US External Video Switch Unit (EVSU) were not carried through the Canadian Mobile Base System (MBS), causing a significant impact due to total loss of video from SSRMS/MBS cameras to the RWS.
- Control Moment Gyros (CMGs) powered down unexpectedly during a US Lab C&C computer switchover; the on-orbit impact would have been regaining control of the US On-orbit Segment (USOS) attitude and using more propellant.
- Other finds worth mentioning are a US Lab C&C Small Computer System Interface (SCSI) bus cabling redesign due to 1553 errors; audio downlink quality issues for accented or foreign language; Solar Array Rotating Joint (SARJ)/Trailing Radiator Rotating Joint (TRRJ) auto-tracking failure due to a GNC software problem; and a US Lab C&C computer failure during sync to GPS time.
- Hundreds of software glitches and problems were found and corrected.

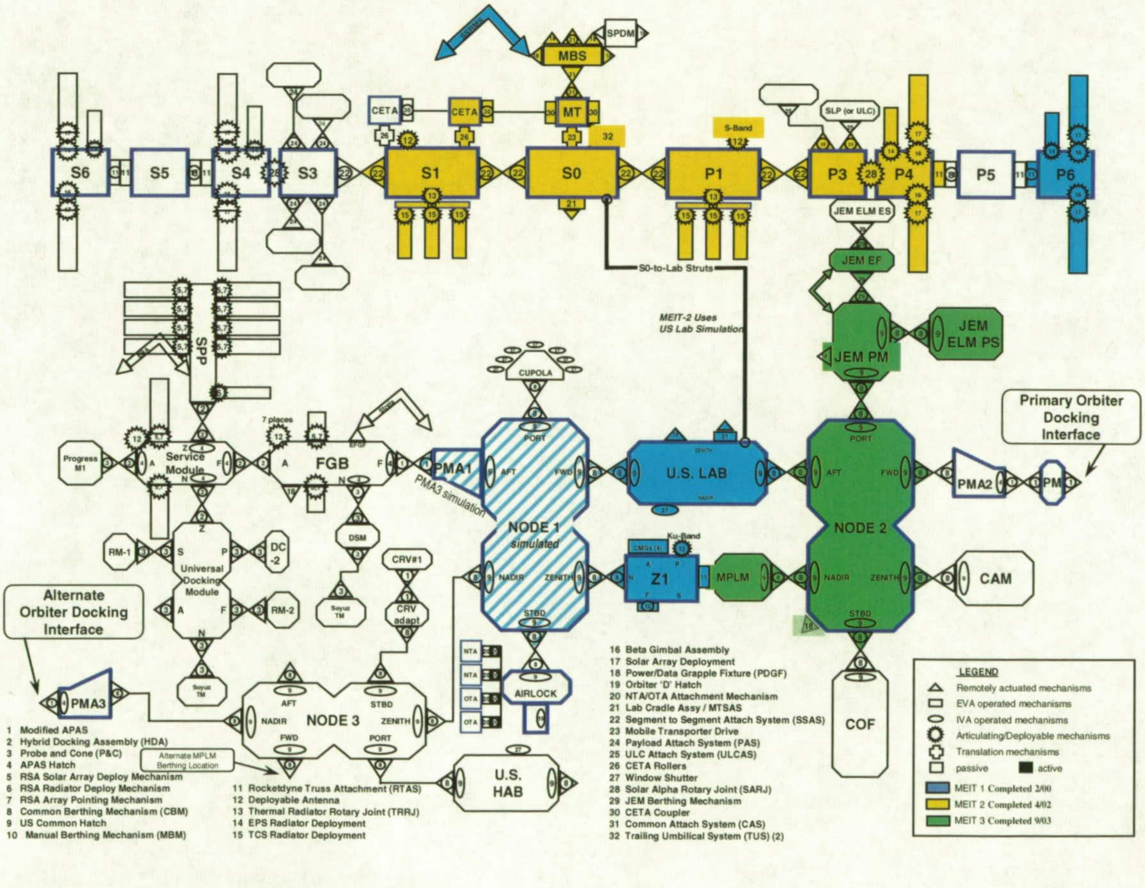

Figure 1. ISSP MEIT Configurations

OTHER MEIT BENEFITS

An invaluable factor is the experience that flight controllers, station crew, International Partners, and engineers have gained from participation. These integration tests have also paced the development of flight activation procedures. A significant number of deviations have been incorporated into flight procedures, preventing failed on-orbit activation and checkout activities. The cumulative effect of identifying and correcting all the integrated hardware/software/procedure problems before flight has saved the ISS Program from major on-orbit failures. Also, in addition to operational impacts, cost and schedule have been saved. Most of these problems would have been far more expensive and riskier to correct on orbit.

FURTHER OBSERVATIONS

There is an interesting point in the history of ISSP MEIT testing. Metrics show that later testing such as Node 2 IST and MEIT3 revealed significant improvements in the software products as well as the hardware delivered from the factory. For MEIT1, a total of 884 Interim Problem Reports (IPRs) were taken, while MEIT2 had 334, and MEIT3 had 64. Some anomalies should have been discovered at the factory level, during qualification and acceptance testing. Not all problems were pure integration testing finds. One could conclude that a more rigorous test program at the element/system level is important for integration testing, to avoid large-scale configurations to find standalone element problems. As a result of using mature hardware and software, integration testing demonstrates on-orbit success for critical flight operations on the ground versus on-orbit, in a cost and schedule effective manner. Therefore, it is notable that the incorporation of requirements, the hardware manufacturing and qualification stages, as well as software development stages are equally as critical as integration and test of the entire system for a mission.

Simulations and emulations of unavailable elements necessary to meet the requirements of the configuration are also important. MEIT developed an ISS Flight Emulator which emulated vital elements for testing purposes. The Software Development Integration Laboratory (SDIL) in Houston, Texas, representing the entire station, was also invaluable for providing hardware and software integration. These simulations allowed verification of the software, the opportunity to perform critical procedure validation prior to testing with flight hardware, reducing the risk of damage to hardware and personnel, and the ability to re-create and troubleshoot on-orbit anomalies. Simulations and emulations are a must for successful testing at various levels of development. Finally, a further improvement to testing should include autonomous information systems, providing real-time payload/vehicle configuration, automatic tracking of test requirements, and instantaneous quality audits prior to the mission.

If integration testing is planned early enough, would it change the development of the hardware design? Possibly hard mating of the elements could have been accomplished with ISS elements, rather than building and procuring expensive jumper cables. The hardware's structural limitations did not allow for orientations necessary to easily perform hardware mates for full functional testing. It should be evaluated during the requirements and design stages if modifications could be accomplished to drastically improve configurations to enable ease of testing and reduce costs.

Integration testing and verification requirements also have significant impacts on facility and GSE development. A single set of standards and specifications should be provided for everyone to utilize during fabrication and assembly. The GSE and facility should be verified thoroughly and certified prior to the arrival of flight hardware. There have been too many instances where the GSE has failed and consumed valuable test time to resolve before the flight article was tested. Having a solid, defendable plan for verification – whether it's factory-level checkout or full functional integration testing – should be defined early enough to have a positive affect on the design of ground and flight systems. The design of GSE, including access, handling, processing and checkout systems, would be enhanced if the test requirements are identified and incorporated early in the development process.

If the flight hardware has been accepted and shipped to the launch site as elements or systems, and fully integration tested, it will still require validation interface testing with interconnect cabling with the launch vehicle. Although the use of simulators (emulators) to replace unavailable hardware assists in earlier testing, the actual interfacing of the mating hardware must be tested prior to launch to assure that all systems are functional and have the required margins for flight.

The on-board software should be baselined prior to the start of integration testing. Software development has typically lagged behind the manufacturing of the hardware. The ISSP has shown repeatedly that a final version software load is one of the last processes before the element is taken to the launch pad. And then a final power up of all components must be conducted to prove the new software load. Early MEIT testing was not afforded the opportunity to run with Flight Qualification Tested (FQT) software. Integration testing should not be the primary test of the flight software. It should be fully integration tested and qualified in a software laboratory prior to an integration test with the hardware.

"For systems requiring incremental assembly where elements involve distributed end-to-end subsystems in low earth orbit or beyond earth orbit, it is prudent to conduct multiple-element integration testing prior to launch. Use of approaches such as testing elements in logical groupings with appropriate fidelity emulations of interfaces is acceptable. The use of emulators is, however, less desirable than testing the actual hardware, and additional care needs to be exercised in the development of interface controls to ensure the emulators reflect the true "as built" configuration of the system. Testing is carried out with software possessing flight functionality and flight hardware in flight configuration. Priority is given to interface validations of hardware and hardware/software interaction. If applicable, end-to-end testing of command and telemetry links between the control center(s) and the vehicle can be accomplished." (NPG 8705.2 Human-Rating Requirements and Guidelines for Space Flight Systems 2005)

A final thought is the notion to use risk analysis to determine if integration testing should be performed. However, the very nature of the inability to predict everything that could potentially occur with multiple elements, modules, and systems, yields this concept as flawed. When systems cross organizational, contractual, or geographic boundaries, integration testing becomes imperative. "The risks inherent in these technical systems are heightened when they are produced and operated by complex organizations that can also break down in unanticipated ways". (CAIB Report 2003).

TRANSITIONING THE LEGACY TO THE CONSTELLATION PROGRAM

Integration testing is defined as testing that occurs between two or more individual Constellation systems to verify the interfaces between those systems, and to validate the integrated systems' functionality and interoperability. Integration testing applies to the in-space flight and integrated vehicle stack configurations including multi-element integration testing (MEIT), flight element integration testing (FEIT), and interface verification testing (IVT).

For clarification, it should be noted that for the Constellation Program, systems are comprised of elements, such as the Service Module, the Crew Module, the Launch Abort System are all elements of the Crew Exploration Vehicle (CEV) (Orion spacecraft). The First Stage and Upper Stage are elements of the Crew Launch Vehicle (CLV) (Ares I rocket). Examples of the system would be the CEV or the CLV, while for ISSP, the US Lab, Node2, and the P6 truss are elements. Figure 2 depicts the system, element, and subsystem breakdown of the Constellation architecture. The terms "MEIT" and "FEIT" are legacy terminology and have been adopted by the Constellation Program. For Constellation, the terms are used to indicate multi-"system" and flight "systems" tests instead of multi-"element" and flight "element" tests.

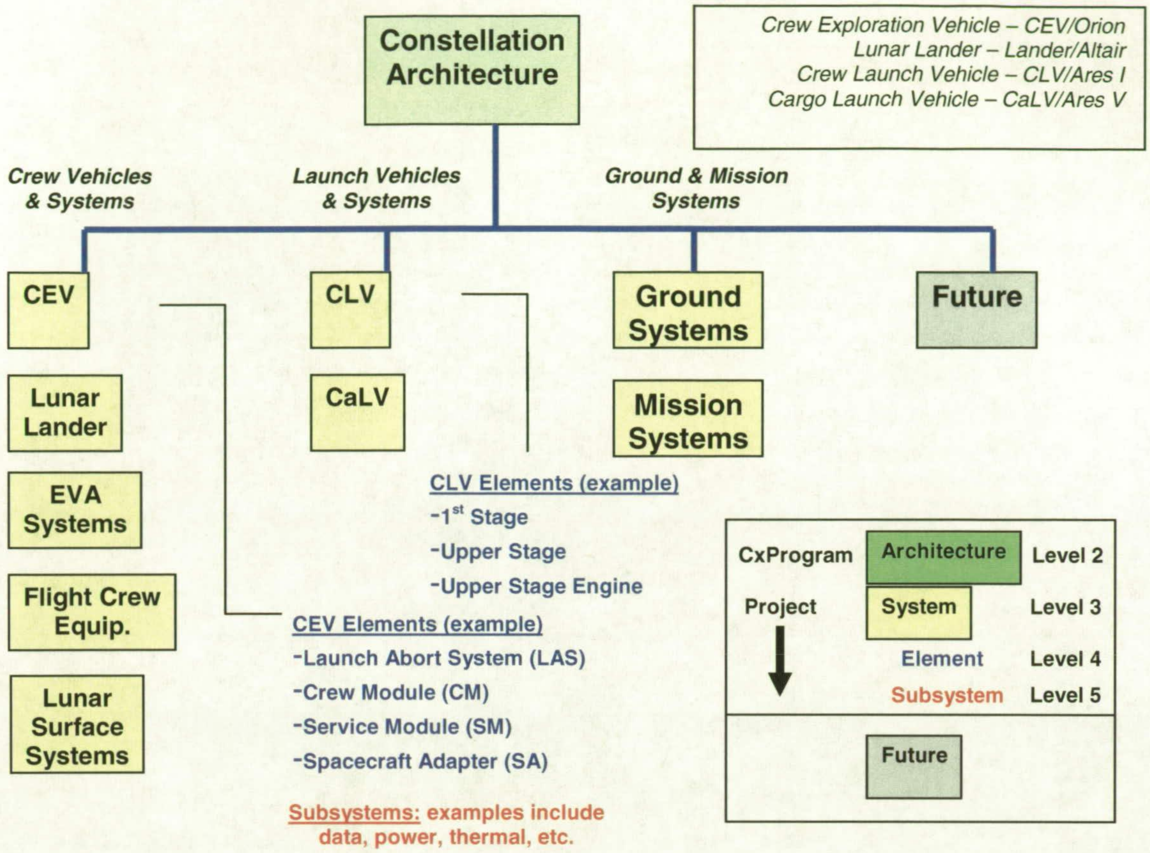

Figure 2. Constellation Program Architecture Systems, Elements, and Subsystems.

MEIT

As already understood by the context of the paper, MEIT is an integration test between two or more flight systems that will be launched on separate vehicles and integrated together for the first time in space. Interfaces between the flight systems, mission systems, and other appropriate Constellation Program (CxP)/ISSP and external systems may also be tested as part of each MEIT.

Primary objectives of MEIT for this program are to demonstrate interoperability, functionality, and stability of the flight systems, elements, and subsystems as an integrated "in-space" vehicle assembly on the ground before they are assembled in space for the first time. Critical mission sequence activities and flight procedures will be validated prior to their first-time execution in flight.

A secondary objective of MEIT is to collect functional and performance data from the integrated flight systems to support validation of the different interface test tool sets, emulators, and simulations used by the projects in accepting future serial numbers of those flight systems.

MEIT also serves as a training ground for flight crew and trainers. The Mission Operations Division (MOD)/Mission Control Center (MCC) personnel gain great experience during these activities.

A critical point is that MEITs are executed after all of the system-level requirements have been satisfied by the respective project offices, and they have declared their system designs as verified for flight. All System Requirement Document (SRD) and Interface Requirement Document (IRD) verification requirements have been closed, thus rendering MEIT a validation test, operating as closely as possible to flight scenarios. CxP MEITs, performed prior to first crewed missions of the ISS and Lunar blocks, are one-time tests with a potential for follow-on regression testing.

At the writing of this paper, two planned MEITs are documented as depicted in Figures 3 and 4.

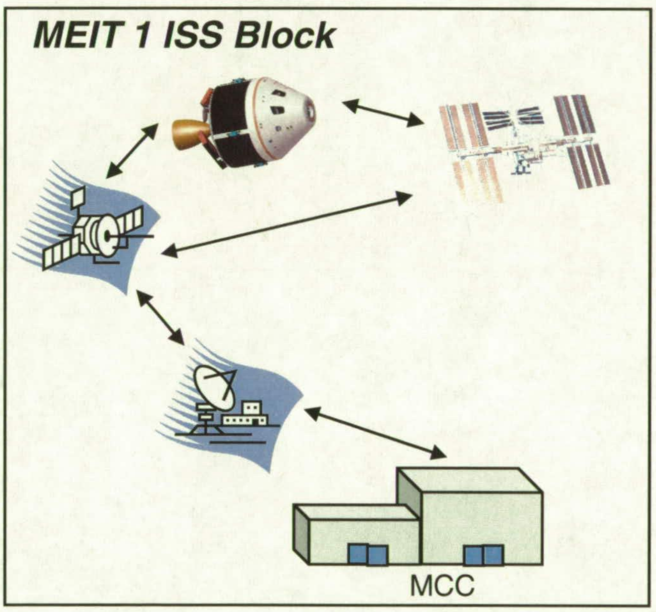

Figure 3. Crew Exploration Vehicle (CEV) to International Space Station (using ISS emulation) – Orion/ISS, and includes Mission Control Center (MCC), TDRSS, ground station.

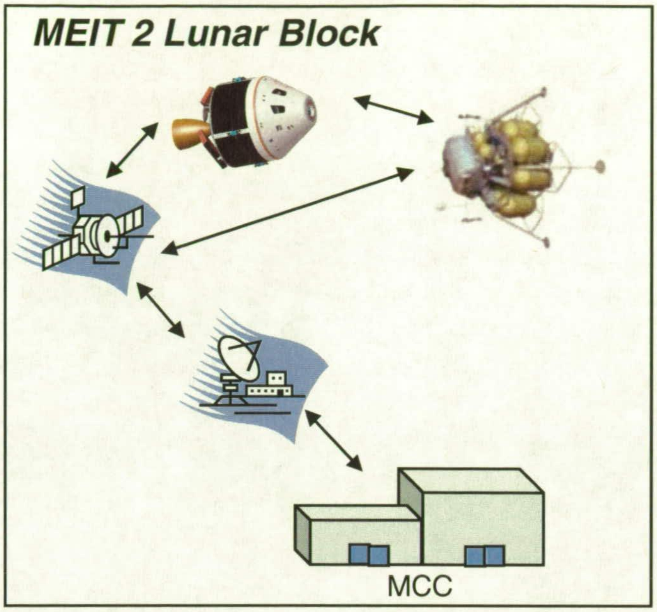

Figure 4. CEV to Lunar Lander/Earth Departure Stage (EDS) (using EDS emulation) – Orion/Lunar Surface Access Module (LSAM), and includes Mission Control Center (MCC), TDRSS, ground station.

The Lunar block MEIT may contain multiple configurations since it is intended to validate inter-system interfaces and functionality in both the launch and Low Earth Orbit (LEO) configuration (CEV to LSAM/EDS), as well as the post Trans-Lunar Injection (TLI) configurations after EDS jettison (CEV to LSAM), and then CEV to LSAM ascent stage, to validate the configuration after the ascent stage returns from the moon and re-mates with the CEV without the descent stage.

FURTHER DEVELOPMENT OF MEIT1 (ISS-CEV) TEST OBJECTIVES

As the program delves further into test objectives development, more detailed requirements will emerge. Objective examples are as follows:

- The program will verify audio quality, frequency response, and harmonic distortion for all audio signals in mated configuration (air-air, air-ground, intercom, page key, page voice)
- Acceptable video quality and signal characteristics for all baseband links between CEV and ISS
- Audio quality, frequency response, and harmonic distortion for both directions over open loop CEV-ISS S-Band RF links
- Packet loss testing of open loop CEV-ISS S-Band RF link with signal level set to minimum and maximum limits for both forward and return links

- Peak power bus currents for each feed in mated configuration to not exceed maximum value for both active and quiescent modes
- Transient, steady state, ripple, noise, and source/load impedance comply with power quality standards
- Simulated on-orbit rendezvous and docking operations (signal acquisition, Guidance, Navigation and Control (GNC) moding, command path switching)
- Simulated on-orbit CEV state/mode transitions (active to quiescent, quiescent to active)
- Simulated on-orbit undocking and separation operations
- Health status software upload to CEV
- First flight to station (Orion 1) demonstration of proximity operations capability
- Capability to support dual CEV docked and undocked operations
- CEV reception and process of commands generated from Portable Computer System (PCS) laptops and commands generated from MCC-H and transmitted via ISS S-Band
- Proper file/memory transfer between CEV and local ISS C&DH systems (PCS, C&C mass storage device (MSD), Space Station Complex (SSC))
- Proper file/memory transfer between CEV and MCC-H via ISS S-Band
- CEV telemetry processes and displays on PCS laptops
- CEV telemetry received via ISS S-Band can be processed and displayed at MCC-H
- CEV acquisition and synchronization to time broadcast from ISS
- IP packet and 1553 message loss for all Gigabit Ethernet/1553 channel combinations in mated configuration
- IP packet transmission routing and packet loss between CEV and ISS Integrated Station LAN

More objectives will be developed, and from the objectives, many more detailed test and verification requirements will result.

FEIT

Flight Element Integration Test is defined as testing between new or significantly modified systems and elements being assembled into an integrated launch vehicle for the first time. Interfaces between the flight systems, ground systems, mission systems, and other appropriate CxP and external systems may also be tested as part of each FEIT.

The primary objectives of FEIT are to demonstrate the interoperability, functionality, and stability of the flight systems, elements, and subsystems as an integrated "launch vehicle" stack assembly prior to the first operational test flight of that particular launch vehicle configuration. Critical mission sequence activities and flight procedures will be validated prior to their first-time execution.

A secondary objective is to collect functional and performance data from the integrated flight systems to support validation of the different interface tool sets, emulators, and simulations used by the projects in accepting future serial numbers of those flight systems.

As with MEIT, FEITs are executed after all of the system-level requirements have been satisfied by the respective project offices and those projects declare their systems designs as verified for flight. FEITs are planned as part of the assembly and processing of the integrated launch vehicle. FEITs are planned for every test flight, with the exception of the Ares1-X test flight, which is a demonstration flight to inform the design of the vehicle.

FEITs are planned as follows:

- For Ares1 (ISS Block): Crew Exploration Vehicle/Crew Launch Vehicle (CEV/CLV) – Orion/Ares1, and includes Mission Control Center (MCC), Launch Control Center (LCC), TDRSS, ground station, ground systems.

- For Ares V (Lunar Block): Lunar Lander/Earth Departure Stage/Cargo Launch Vehicle (LSAM/EDS/CaLV) – LSAM/EDS/Ares V, and includes Mission Control Center (MCC), Launch Control Center (LCC), TDRSS, ground station, ground systems.

INTERFACE VERIFICATION TESTING (IVT)

Interface Verification Testing (IVT) performs mechanical, data, and electrical interface verification and validation between two or more flight systems after these systems have been mated. It consists of the minimal set of activities to confirm the integrity of all physical and functional interfaces between systems involved for each specific vehicle stack configuration. IVTs are performed as a subset of the FEITs during the early flight tests and then performed for every flight after Full Operational Capability (FOC) has been obtained for both flight and ground systems. This is the testing that will occur for all nominal missions for the duration of the program.

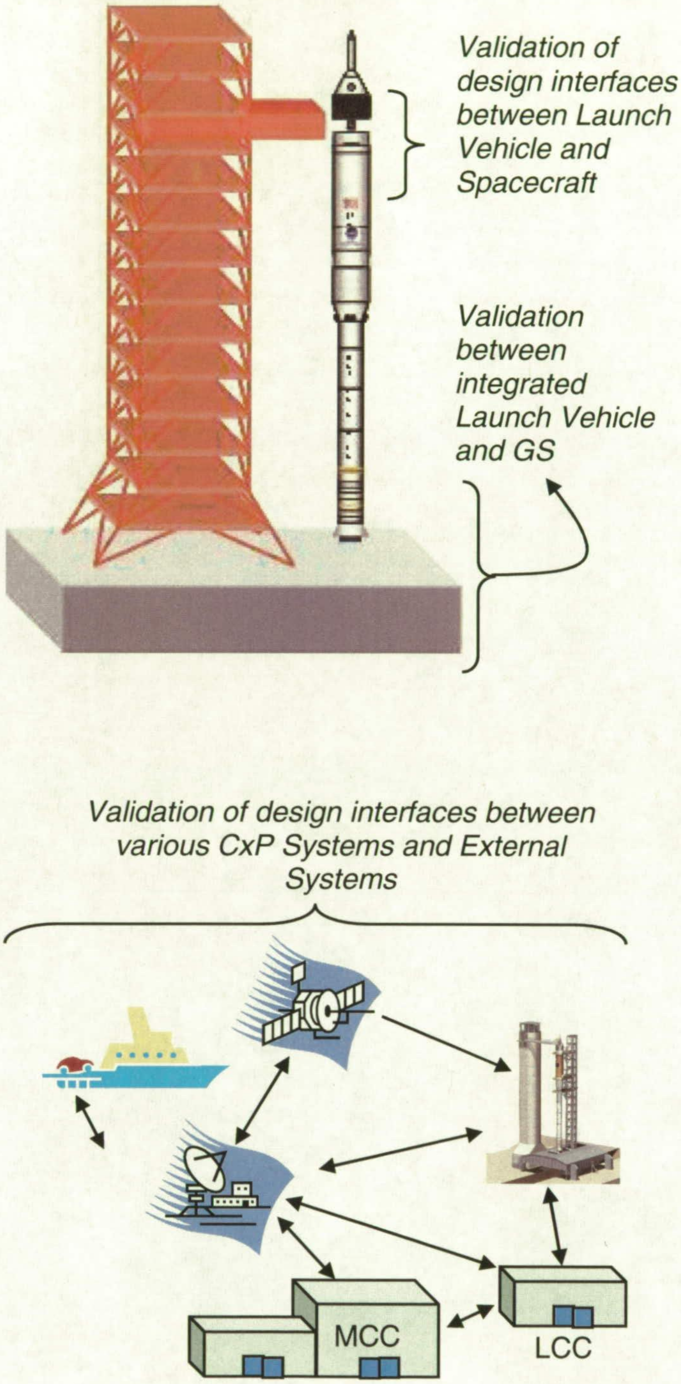

Figure 5. Validation of Interfaces Between Systems and CxP and External Systems.

A DIFFERENT TESTING APPROACH FOR CONSTELLATION

While testing is usually recognized as an important part of a project, it does not typically receive the attention that is needed until late in the development flow, nor is it afforded the required funds early on and throughout the life of the program. "Testing in general does not receive as much attention as it should in order to ensure a project's success. First, testing typically does not receive enough emphasis during the initial planning phases. Life-cycle cost estimating is another area that should be enhanced and used in making test decisions. When the cost of on-orbit repairs are considered in the decision, it often becomes apparent that performing a test is money well spent in the long run." (Britton and Schaible 2003, 63, 65). The Constellation Program has shifted the paradigm by developing a separate test and verification organization, and developing the strategies, concepts, and guidelines at the beginning of the program. This includes development of a correlating verification requirement for every requirement at each design level. Furthermore, a building block approach, from early development to qualification, acceptance, validation integration testing, and flight testing is being implemented. Therefore, the schedule, budget, and technical requirements for integration testing are being understood and accepted early in the program. This culture change will drive mission success.

CONCLUSION

In conclusion, the examples stated in this paper, describing the type of anomalies encountered at the launch site, are well-documented evidence of problems that could have only been found in an integrated configuration, as well as other problems that should have been found in stand-alone testing at the factory. Emphasis should remain upon a fully completed and verified element or spacecraft leaving the factory for delivery to the launch site, while subsequently performing an end-to-end multi-element integration test and flight element integration test of the entire system after delivery to the launch site prior to its' journey into space. To ensure a successful mission, it is imperative that time in the schedule and budget allowances permit this testing. The integration testing process has evolved into an efficient, cost effective means of ensuring risk mitigation to the ISSP, and will accomplish the same goals for the Constellation Program.

"Standing alone, components may function adequately, and failure modes may be anticipated. Yet when components are integrated into a total system and work in concert, unanticipated interactions can occur that can lead to catastrophic outcomes". (CAIB Report 2003)

REFERENCES

Keith J. Britton, Dawn M. Schaible, "Testing in NASA Human-Rated Spacecraft Programs: How much is just enough?", Massachusetts Institute of Technology Thesis, February 2003

NASA Columbia Accident Investigation Board (CAIB) Report Volume I, August 2003

NASA Office of Safety and Mission Assurance, NPG 8705.2 Human-Rating Requirements and Guidelines for Space Flight Systems, February 2005

BIOGRAPHIES

Ms. Sowards is currently the Test & Verification Manager for the NASA Constellation Ground Operations Project at the Kennedy Space Center, where she is responsible for verification requirements development and closure, multi-element and multi-system integration test concept and planning for both ground systems and flight systems, and defining the fundamental guidelines and approaches of test and verification for Constellation at KSC. In support of early development of the new Constellation Program, Stephanie supported NASA's Exploration Systems Architecture Studies (ESAS), led a study on integration and flight testing, managed the Test & Verification Integrated Product Team for the Program, and began development of a strategy and philosophies to implement an integrated and comprehensive approach for verifying new space vehicles and elements. Stephanie worked several years for the International Space Station Directorate at KSC, performing various roles in Multi-Element Integration Testing (MEIT), including Command & Data Handling Systems Engineer, ISS emulators and simulation test configuration Project Lead, Lead Integration Engineer, and Test Site Activation Lead. She graduated from the University of Central Florida with a Bachelors of Science Degree in Computer Science.

Mr. Honeycutt started his career with NASA at the Kennedy Space Center (KSC) in 1990, shortly after his graduation from Auburn University. He currently works in the KSC Ground Operations Project Office leading the planning of integrated Test and Verification (T&V) activities at KSC for the Constellation Program (CxP). He also provides leadership and technical management in defining verification strategies and requirements for ground systems used to perform ground operations at the launch, landing and retrieval sites. He serves as the primary technical interface between the CxP and KSC concerning integrated T&V issues. Earlier in Tim's career, he worked numerous years for the International Space Station (ISS) Directorate at KSC. He performed various roles in the ground processing of flight hardware, including Multi-Element Integration Testing (MEIT) of ISS flight elements and the development of ground support equipment. Tim also worked in the Design Engineering Directorate at KSC as a Senior Communications Engineer.