STRATEGIES FOR GROUND BASED TESTING OF MANNED LUNAR SURFACE SYSTEMS

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ABSTRACT

One of the primary objectives of NASA's Vision for Space Exploration is the creation of a permanently manned lunar outpost. Facing the challenge of establishing a human presence on the moon will require new innovations and technologies that will be critical to expanding this exploration to Mars and beyond. However, accomplishing this task presents an unprecedented set of obstacles, one of the more significant of which is the development of new strategies for ground test and verification. Present concepts for the Lunar Surface System (LSS) architecture call for the construction of a series of independent yet tightly coupled modules and elements to be launched and assembled in incremental stages. Many of these will be fabricated at distributed locations and delivered shortly before launch, precluding any opportunity for testing in an actual integrated configuration. Furthermore, these components must operate flawlessly once delivered to the lunar surface since there is no possibility for returning a malfunctioning module to Earth for repair or modification. Although undergoing continual refinement, this paper will present the current state of the plans and models that have been devised for meeting the challenge of ground based testing for Constellation Program LSS as well as the rationale behind their selection.

KEYWORDS:

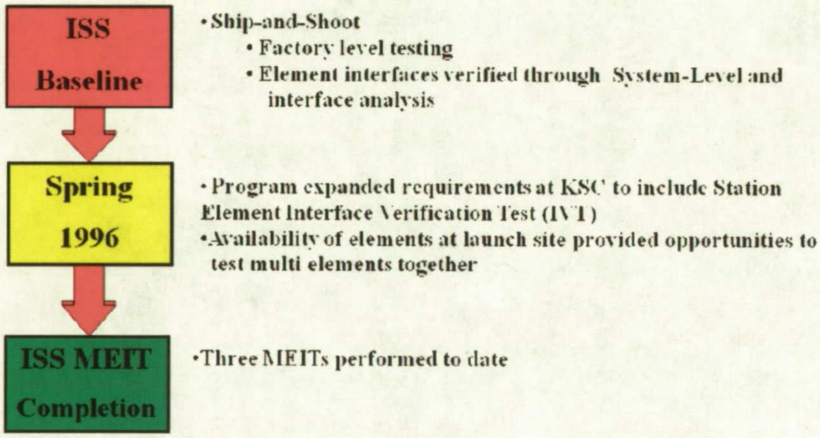
Multi-Element Integration Testing (MEIT), Interface Verification Testing (IVT), Verification, Validation, Test, Emulator, Simulations, Qualification, System, Element, Lunar Systems.

INTRODUCTION

The International Space Station Program (ISSP) baseline originally intended the Station element hardware to be a ship and shoot philosophy. Factory level testing and element interface verifications at the subsystem-level, and interface analysis was 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. The 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. This was the development of the concept of the Multi-Element Integration Test (MEIT).

The MEIT is a risk mitigation effort to test beyond individual element level acceptance testing that verifies the operation of flight element systems (hardware and software) in an environment that is as flight-like as possible. The MEIT demonstrates the Space Station Element to Element interface compatibility and Systems End to End operability and functionality.



- Ship-and-Shoot
  - Factory level testing
  - Element interfaces verified through System-Level and interface analysis
- Program expanded requirements at KSC to include Station Element Interface Verification Test (IVT)
- Availability of elements at launch site provided opportunities to test multi elements together
- Three MEITs performed to date

Figure 1. MEIT Program Development

ISSP TEST CONFIGURATIONS

Three Multi-Element Integration Tests and one Integration Systems Test (IST) were conducted for the ISS.

- 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.
- MEIT3 included the Japanese Experiment Module, Node2, and the US Lab emulator
- Node2 IST was comprised of Node2 and US Lab and Node1 emulators, as part of the ISS Flight Emulator.

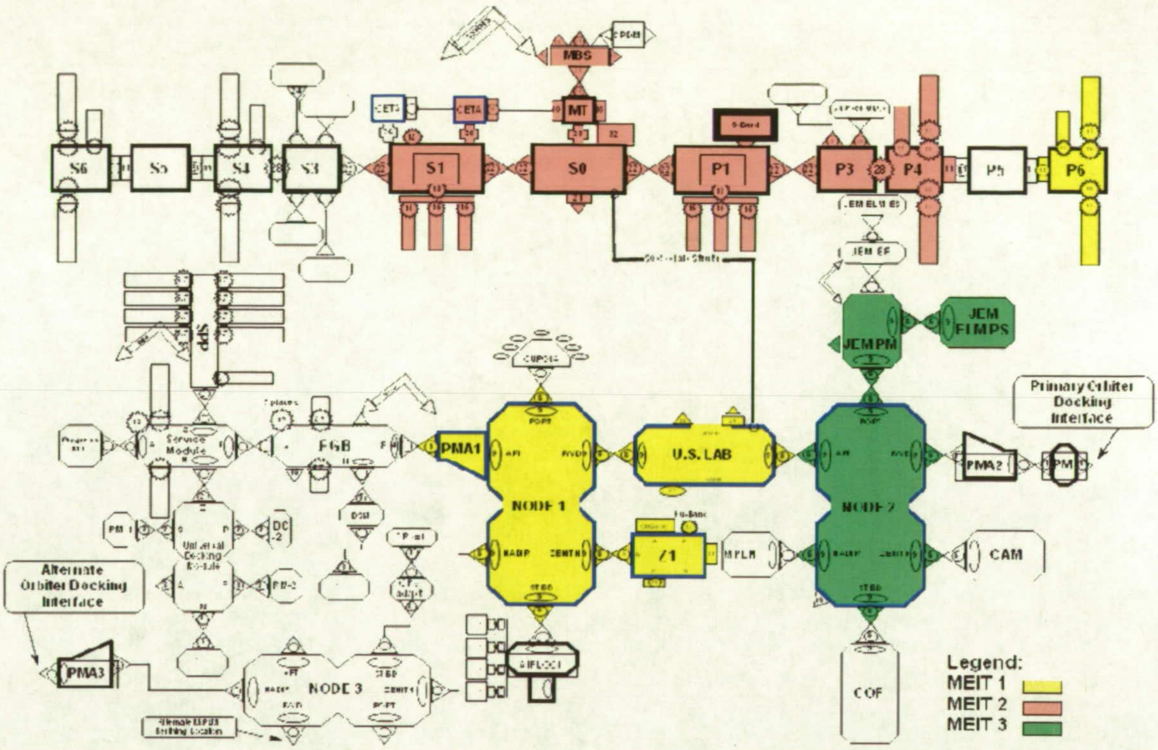


Figure 2. MEIT Test Configurations

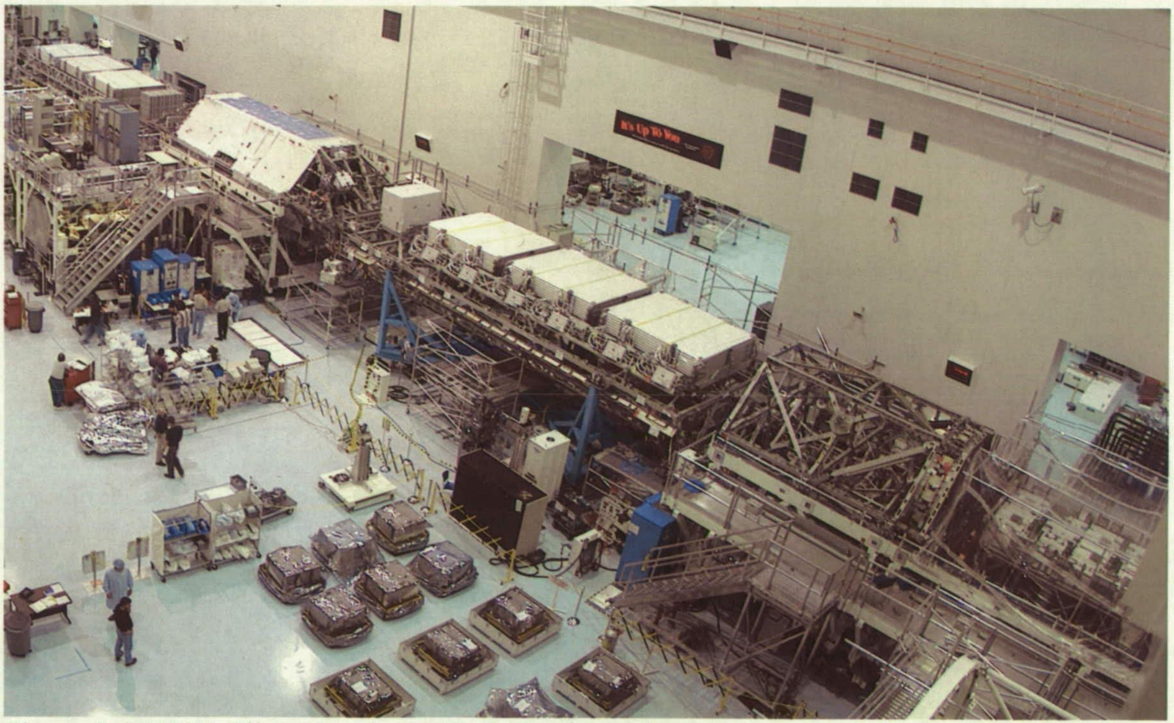


Figure 3. MEIT2 Flight Hardware Test Configuration

ISSP MEIT MAJOR FINDS

During the multi-element integration tests conducted, 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 with the potential for the loss of the mission, loss of the element or possibly loss of crew. Some of the problems found and corrected during ground testing and their potential impact to assembly operations are as follows:

- 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.
- 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.
- 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.

ISSP LESSONS LEARNED APPLIED TO THE CONSTELLATION PROGRAM

The Constellation Program is applying the lessons learned from the ISSP MEIT's. It has implemented a new testing philosophy of the Orion/Aries launch vehicle elements. The Constellation Program has structured a standalone test and verification organization, within the Program as well as each Project, and developing the strategies, concepts, and guidelines at the beginning of the program. Rather than waiting too late in the development flow to resolve element integration issues, the Constellation Program is funding integrated testing early on and throughout the life of the Program. This process forms a building block approach that stretches from early development to qualification, acceptance, validation integration testing, and flight testing. Allowing for the schedule, budget, and technical requirements for integration testing to be better understood and accepted early in the program life cycle.

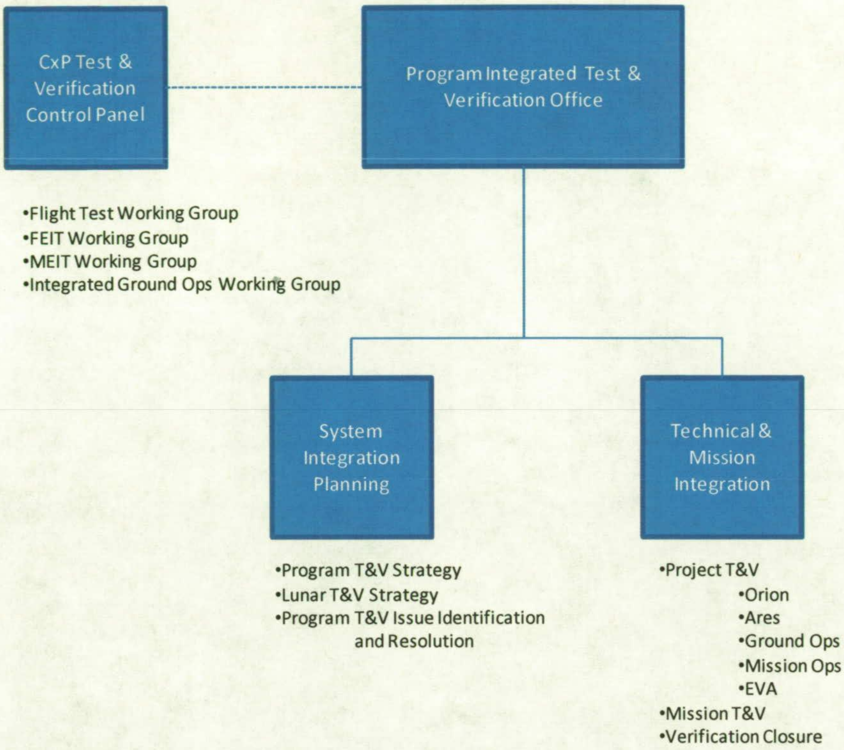


Figure 4. Constellation Program Test and Verification Organization

MEIT TESTING SCENARIOS FOR THE CONSTELLATION PROGRAM

Based upon the set of Design Reference Missions (DRMs) currently established for the Constellation program, three possible candidate configurations for MEIT testing have been identified:

Orion to ISS: The Orion to ISS MEIT test is currently planned to be performed as part of the ground processing flow for the Orion 2 mission and will be conducted at approximately launch minus six months. It will include the Orion 2 flight vehicle upon turnover to Ground Operations after completion of all formal acceptance and qualification testing and prior to servicing with hazardous commodities. At the current time it is envisioned that this MEIT test is a one time only event, however significant modifications or upgrades to Orion avionics or flight software interfaces will be evaluated for potential impacts that might necessitate the need for regression testing. ISS interfaces and functions will be represented by use of the existing ISS Flight Emulator specifically tailored to support the subset of avionics capabilities appropriate to Orion and outfitted with additional components (ISS-CEV Communications Adapter and ISS S-Band RF Assembly) currently under development to support the new set of interfaces unique to the CEV. Note that proper operation of these devices will already have been demonstrated on-orbit during the Orion 1 mission prior to this MEIT test.

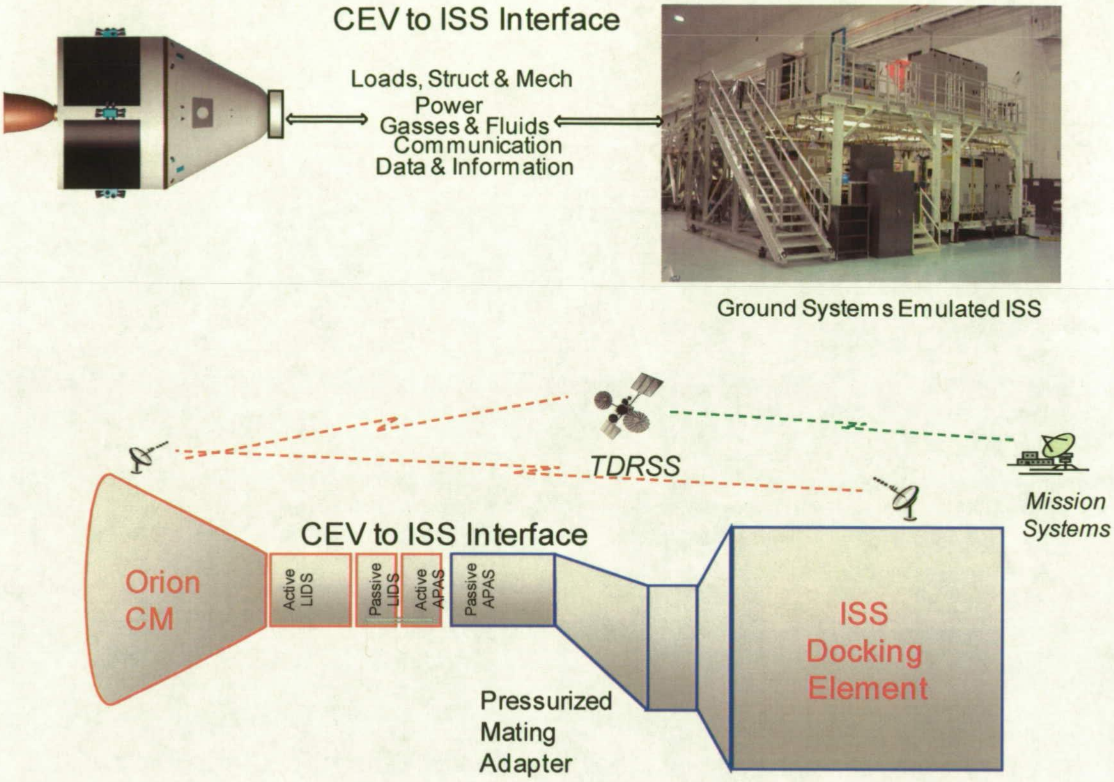


Figure 5. Orion to ISS MEIT Configuration

Orion to Altair: The Orion to Altair MEIT test is intended to serve as a 'dry run' of the combined CEV to lunar lander operations that will occur in Earth orbit during lunar sortie and lunar outpost missions. For both of these missions, the Altair will be launched first by the Ares V Cargo Launch Vehicle into a low Earth altitude parking orbit. Once communications has been established and the Altair module and Earth Departure Stage have successfully completed on-orbit checkout, the Orion will be transported to orbit aboard the Ares I. This MEIT configuration will demonstrate the joint operability between the two modules in both the pre-mated (rendezvous, proximity operations, and docking) and post-mated mission phases. At the present time, it is expected that a flight model of the Earth Departure Stage will not be available for this test configuration, so appropriate emulation capabilities will have to be used instead.

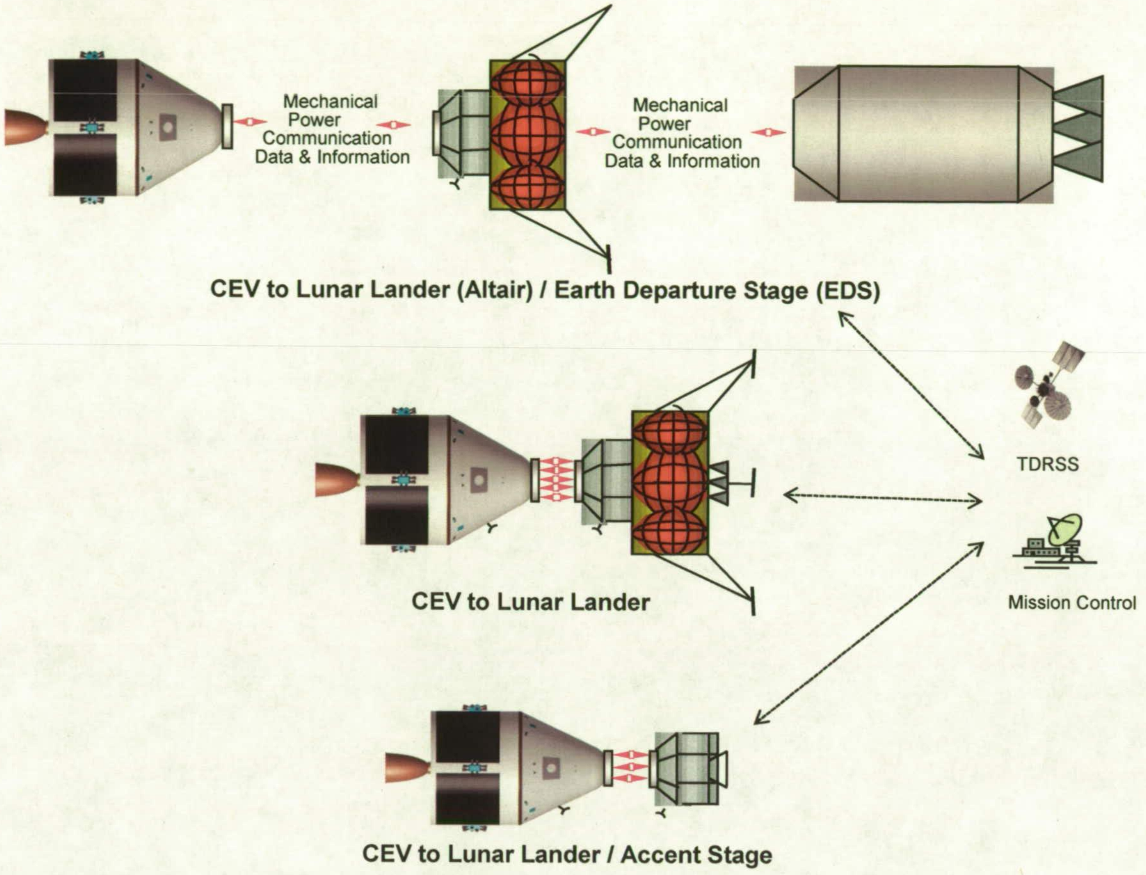


Figure 6. Orion to Altair MEIT Configuration

Lunar Surface Systems MEIT: Lunar Surface Systems (LSS) is a generic term used to describe a set of modular, highly distributed, yet closely coupled components that, when assembled into pre-determined configurations provide all the facilities and resources needed to support an independently sustainable, permanently manned outpost on the surface of the Moon. Some of the different types of these components include science laboratory, logistics, and habitation modules, crew and cargo mobility vehicles, EVA suits, power generation stations, and communications terminals. At the present time these are still considered abstract concepts that will eventually evolve into specific designs as the refinement of mission requirements, maturity of necessary technologies, and long term budget and schedule forecasts become clear. A number of trade studies are already underway to help further this process, such as the analysis of benefits and liabilities associated with hard shell versus inflatable pressurized modules. One of the initial outpost configurations that is a candidate for MEIT testing is shown in the figure below.

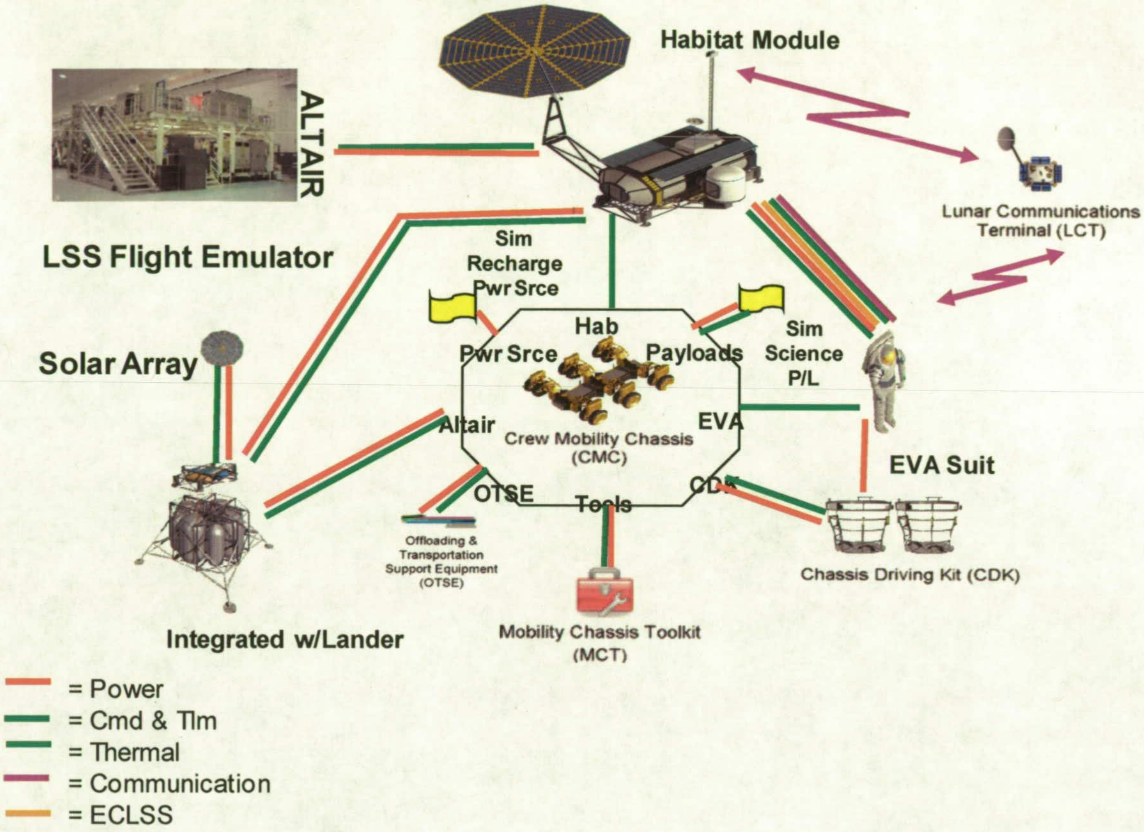


Figure 7. Lunar Surface Systems MEIT

LUNAR SUFACE SYSTEMS OVERVIEW

The Lunar Surface Systems project is managing the development of concept architectures to fulfill the Constellation objective of developing a lunar outpost. The LSS project mission statement is as follows:

"Develop a sustained human presence on the moon to promote exploration, science, commerce, and the United States' preeminence in space, and to serve as a stepping stone to future exploration of Mars and other destinations."

As of summer 2009, there are thirteen scenarios that have been developed by LSS project teams that have allowed the study of various trades and options that could affect the characteristics of lunar surface systems. Scenarios are effectively mission architectures encompassing a series of launches and mission operations that form a lunar outpost. An example of these trades is an evaluation of whether the outpost should be mobile or fixed. Factors that affect that trade are the range of the crew on Extra-Vehicular Activities and/or on lunar rovers to do science, the amount of science activities that can occur in the range of an outpost, and mobility options that would allow the entire outpost to be mobile. For example, the ATHLETE (All-Terrain Hex-Legged Extra-Terrestrial

Factors that affect that trade are the range of the crew on Extra-Vehicular Activities and/or on lunar rovers to do science, the amount of science activities that can occur in the range of an outpost, and mobility options that would allow the entire outpost to be mobile. For example, the ATHLETE (All-Terrain Hex-Legged Extra-Terrestrial Explorer) robotic vehicle could be used to transport the lunar habitat while lunar rovers could transport the crew and other equipment.

Figure 8. A one third scale ATHLETE undergoing tests in a desert analog lunar environment. (Ref 3)

Another element of the potential lunar architecture is the Lunar Electric Rover (LER). This rover is based on a Mobility Chassis (MC) with a Pressurized Crew Cabin (PCC) mounted atop of it. The Mobility Chassis can alternatively have Crew Driving Kits (CDKs) mounted on it to allows EVA suited crew members to drive the MC. But having the PCC allows lunar outpost astronauts to have a shirtsleeve working environment aboard a mobile lunar rover. The first prototype of the LER was famously seen at the end of the Inaugural Parade on January 20, 2009, where the LER did some maneuvers and then a suited astronaut dismounted from a suit-port at the rear of the LER and saluted President Obama before continuing.

Figure 9. During the 2008 Desert RATS tests at Black Point Lava Flow in Arizona, engineers, geologists and astronauts came together to test NASA's new NASA's Lunar Electric Rover. Image Credit: Regan Geeseman (Ref 4)

Another significant trade involves the technology for the outpost power system. If a nuclear reactor powers the outpost, that probably drives a fixed location. However, with a constant nuclear power source, the lunar day and night cycles are no longer factors that drive crew stays as they might be for a solar powered outpost, and the primary power system becomes less complicated because battery storage won't be required. Another example is the evaluation of the feasibility of utilizing the lunar outpost purely as a pathfinder for outpost systems for an eventual Mars deployment. This requires tailoring systems for robustness for Mars that may not necessarily be required for the Moon but may cut later development costs for Mars applications.

Another evaluation technique being utilized in the lunar architecture analysis is analog testing of a lunar environment in desert locales. Running through potential "day in the life" scenarios at a lunar outpost with prototype equipment allows designers insight into the utilization of the proposed systems and refines architecture and operations concepts. A series of Desert Research and Technology Studies (RATS) have been held in locations such as Moses Lake, Washington and Black Point Lava Flow, Arizona, where the most recent test in June 2008 was performed with the LER where three day excursions were practiced. The 2009 session of Desert RATS is planned for Black Point Lava Flow again where two LERs will operate together and allow for a fourteen day mission. Early plans for 2010 will add a full scale lunar habitat prototype to the two LERs to allow for a thirty day mission.

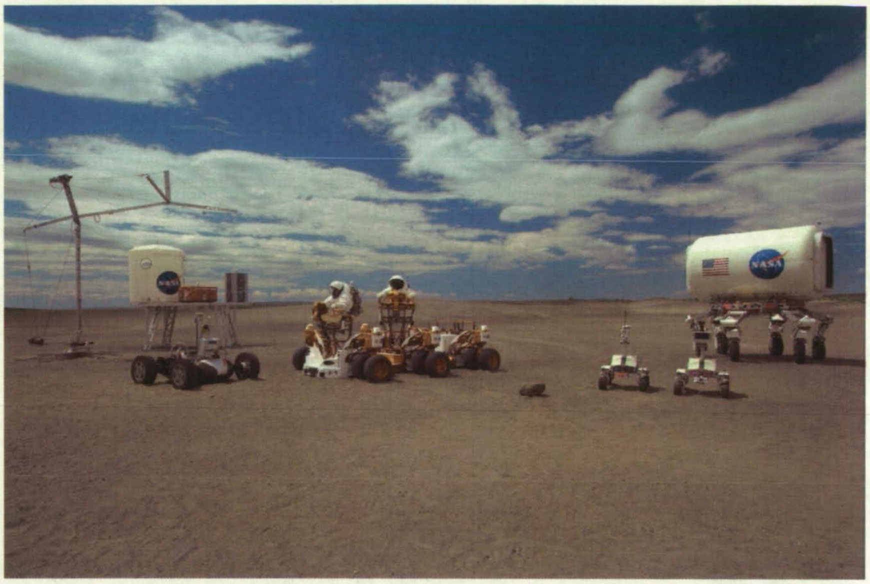


Figure 10. Lunar architecture elements under evaluation during Desert Research and Technology Studies (RATS) field testing at Black Point Lava Flow, Arizona in June 2008 (Ref 5)

Development of the lunar surface systems themselves is seen as a collaborative operation among international partners with governmental and commercial participation. No formal agreements have been made on what participants will develop which systems, and this is an area that will continue to mature as decisions are made on the outpost architecture.

While the exact configuration of lunar surface systems hardware will depend on the outcomes of the trades, field tests, and the results of the scenario analyses, once the configurations are finalized, they will need to be transported to the Moon. There are three notional configurations for the Altair lunar lander, two crewed versions and one cargo version. The crewed version for a Sortie mission includes a Descent Module, an Ascent Module, and an Airlock. The crewed version for an Outpost mission won't include the Airlock since it will utilize one in place at the outpost. The cargo version of Altair will include the same Descent Module, featuring a large deck on which to install lunar surface systems payloads. With the size of the Ares V shroud at 10m, and the potential to fill that volume with an Altair Descent Module up to 9m in diameter (due to dynamic loading allowances), lunar surface systems can potentially be quite large. The crewed versions of Altair will contain a limited amount of cargo capability for small lunar surface systems such as communications equipment, logistics, and science payloads. There may also be future alternatives for lunar surface systems to be transported to the Moon by commercial or international partners.

STRATEGIES FOR INTEGRATED TESTING OF LSS COMPONENTS

The parallels between on-orbit construction of the ISS and assembly of a set of components on the lunar surface capable of supporting long term human occupancy are obvious. Both require seamless integration and interoperability of each component the first time with little recourse for resolving, and potentially disastrous consequences for incompatibilities. It therefore comes as no surprise that the leadership of the Constellation program has already taken steps to make MEIT type testing an integral part of the overall test and verification strategy. Many of the lessons learned from successes and mistakes seen during ISS testing have been identified and incorporated into planning for current and future elements of the Constellation program. These include:

- Identify needs and opportunities for integrated testing early on in program planning
- Incorporate sufficient margins are built into integrated schedules to perform testing
- Establish integrated test working groups during system definition phase with representation from all stakeholders
- Ensure adequate budgets for development and production of necessary resources are identified and built into costs baselines
- Drive capability and support requirements down into prime and sub contract language
- Participate in flight and ground system requirements and design reviews to ensure tools and resources necessary to implement integrated testing are included in baseline architecture
- Identify and plan for long lead time items, such as emulators requiring flight like or functional equivalent units, and new facilities/facility modifications
- Coordinate test planning with flight software production schedules to ensure availability of products that have completed verification and accumulated a significant amount of run time
- Make maximum use of actual ground segment capabilities for integrated testing, including Mission Control Center, SCaN/NISN, TDRSS, and Deep Space Network

PRELIMINARY TEST OBJECTIVES

Although specific test requirements are highly dependant on details of the design, interfaces, and operation of the LSS subsystems, potential candidates for test objectives that are typical of previous MEIT testing include the following:

- Telemetry data reception and processing; validating end-to-end operability by demonstrating proper handling of measurement data with different message formats and content
- Proper generation, transmission, validation, and execution of commands sent from both local and remote sources across RF and hardline links
- Exercise software reconfigurations, updates, and file transfers between source and destination processors

- Demonstration of transmission and reception of audio and video signals with acceptable quality
- Power bus quality and characteristics, including verifying proper voltage and current levels between sources and loads, expected load profiles, impedance and transients measurements, etc.
- Demonstration of correct performance of selected automated fault detection, isolation, and recovery scenarios across multiple components
- Validate startup and initialization sequences and procedures from a cold start to nominal operating conditions
- Radio frequency link characterization, including validation of signal levels, bandwidth, and signal-to-noise ratios
- Characterization and validation of compatibility of thermal loads between heat sources and cooling systems

LSS OPERATIONS CONCEPTS

The ground processing scheme for lunar surface systems will likely bear a great resemblance to the scheme for International Space Station elements. As various elements of the ISS were flown on separate space shuttle missions over many years as cargo payloads culminating in the assembled configuration of the Station, the various elements of lunar surface systems will be flown on separate Altair missions over many years to culminate in the assembled version of the lunar outpost. Additional similarity to ISS will likely develop as the contributions of international partners are added to the mix via outpost systems development and launch alternative options.

The ground processing of lunar surface systems elements as they arrive at the Kennedy Space Center will also be similar to that of ISS elements. As each element arrives, the hardware developer is anticipated to do a post-delivery test to ensure there have been no anomalies induced in the transportation process. Next, that element will undergo any unique servicing or systems testing required to ensure it is ready to support a Multi-Element Integrated Test. Each element will participate in the Multi-Element Integrated Test in the test configurations determined by the MEIT requirements. The test configurations will be addressed shortly. Once complete with MEIT, the element will be removed from the test configuration and once again serviced as necessary to prepare it for installation on the Altair Descent Module. Once mechanically installed, any required fluids umbilicals or cable connections are secured and checked out to verify the interfaces. Once the Altair launch package is completely integrated with its cargo, it will be installed on the Ares V and encapsulated. The Constellation Ground Operations Project at KSC is currently engaged in trade studies to determine the order of hazardous servicing such as hypergolic fuel loading and Composite Overwrapped Pressure Vessel (COPV) filling and encapsulation and in which facilities these activities occur, so the details of those steps cannot be spelled out at this time. Once the integrated Ares V stack is assembled at the Vehicle Assembly Building, any unique interfaces for lunar surface systems elements will be verified though Ares V umbilicals. Like ISS elements, it is anticipated that LSS payloads will have limited electrical interfaces to the carrier, Altair and that heater power may be a common interface. No servicing operations are currently envisioned for lunar surface systems payloads either at the VAB or at the pad.

Back to MEIT test configurations, to determine those test configurations, groupings of payloads for 2-4 launches of Altair will be determined based on test requirements and hardware availability. Those factors will be variables of the eventual LSS mission architecture. It is probably unreasonable to expect hardware to be delivered to the launch site for MEIT more than one year ahead of its need date, but that is a good target to assess whether hardware can be delivered early to make a valuable test configuration. Then after the completion of the initial LSS MEIT test configuration and once the early LSS elements are launched, those early elements must be simulated in a lunar outpost emulator to allow the later elements to virtually interface with already deployed elements of the outpost. This lunar outpost emulator will be managed by workers at the Kennedy Space Center and be comprised of ground servicing equipment and cables, emulator systems provided by flight projects which may be Flight Equivalent Unit systems, and flight and ground software developed by the Constellation programs

The task of ramping up to support an MEIT is spread out over three years.

- Year 1: equipment and long lead item identification; TVR development; technical interchange meetings.
- Year 2: TVR refinement; procedure development and reviews; drawings; critical procedure validation (dry run).
- Year 3: test site activation; test execution; anomaly resolution; test deconfiguration and closure.

REQUIRED GROUND FACILITIES AND INFRASTRUCTURE

A the primary objectives of the planning efforts for ground processing of Constellation program elements is minimizing the need for any new or unique facilities to be constructed at the launch site. Over the past several decades a large amount of complex and expensive buildings and infrastructure have been put in place at KSC to support preparing Space Shuttle and International Space Station flight elements for launch. One of the many ways of helping to control Program cost is to make the greatest use possible of these existing accommodations for processing the next generation of manned spacecraft. A great deal of work continues to be devoted to analyzing the capabilities of legacy facilities and infrastructure to determine where they might be modified for use with Constellation elements. Although currently still under evaluation, a preliminary determination has been made to allocate the Space Station Processing Facility for integrating, testing, and servicing of Lunar Surface System components as well as for performing Multi-Element Integrated Testing. New facilities will be constructed only if current infrastructure will not be able to support emerging requirements. For example, one option under consideration for use as a lunar power source are a series of modular, self contained fission reactors which would impose significant new facility requirements.

One of the more valuable lessons learned from the large scale integrated testing performed for the ISS program is the importance of hardware emulators. For those key

components of highly distributed, tightly coupled systems that will not be able to support a specific test configuration, it is essential that a mockup containing a full set of flight-like representations of on-board functions and interfaces be made available as a substitute. Because these assets typically contain qualification or prototype versions of actual flight avionics units, they are usually quite expensive and involve long lead times for procurement and fabrication. In the Space Station program this need was not widely recognized until relatively late in the overall test campaign, and it proved to be a very expensive and time consuming effort to wait until the first elements had already been launched before starting to field these capabilities. The technical leadership of the Constellation program is fully aware of this potential obstacle and has already made provisions in the budgets and schedules of current and future Program element contracts to account for the design and production of flight fidelity emulators. For example, it has become apparent during early planning for LSS integrated testing that a flight Earth Departure Stage and Altair lunar lander will not be available to support MEIT configurations, so the initial definition phase of this component is already taking into account the requirements for electrical and avionics emulators.
Altair and EDS emulators are expected to be required.
Software must have completed formal qualification testing.
MCC, TDRSS, and DSN are expected to participate to accurately demonstrate end-to-end communications paths

SUMMARY & CONCLUSIONS

Ground processing of modules and elements of the International Space Station presented a unique set of challenges that had not been previously encountered. For the first time in the history of manned space flight, a spacecraft to be placed into Earth orbit was to be of such size and complexity that the opportunity to completely assemble and test the final configuration on the ground prior to launch of the first components was not possible. Each element relied on a collection of tightly coupled interfaces to the segment(s) it was connected to, but in most cases the adjoining pieces were either already on-orbit or had not yet been delivered to the launch site. Furthermore, the serial nature of the assembly sequence required that each element interoperate flawlessly with the existing stage configuration when delivered and installed in space. To return a component to Earth for repairs or modifications needed to resolve incompatible interfaces presented unacceptable costs and schedule impacts to remaining assembly flights. The long list of significant discrepancies discovered during MEIT testing on the ISS program is ample proof that this type of large scale, highly integrated demonstration of end-to-end system interoperability is of invaluable benefit to minimizing the risk of encountering unforeseen discrepancies during assembly and operation in space. It serves as a perfect example of the 'test like you fly' approach.

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BIOGRAPHIES

Mr. Beyer works for NASA in the International Space Station & Spacecraft Processing Directorate at the Kennedy Space Center in Florida. Mr. Beyer has over 20 years of experience in aerospace testing and project management. Currently, Mr Beyer is responsible for leading the effort to infuse the Multi-Element Integrated Test (MEIT) philosophies and capabilities into the Constellation program. He holds a BS in Mechanical Engineering from Florida Tech and a MS in Industrial Engineering Project Management for the University of Central Florida.

Mr. Gill works for NASA in the Constellation Project Directorate at the Kennedy Space Center. He has twenty years of experience on space shuttle payloads and space station elements and experiment payloads gaining valuable experience doing "hands-on" work on flight and ground support hardware and working with people from all over the United States and the world. Currently, Mr. Gill is supporting Lunar Systems development including launch processing infrastructure and flight systems design of Altair and Lunar Surface Systems. He holds a BS in Electrical Engineering and an MS in Aerospace and Mechanical Systems from the University of Florida, an MS in Space Systems from Florida Tech, an MS in Aerospace and is a graduate of the International Space University Summer Session Program in 2006.

Mr. Peacock is currently employed by the Boeing Company at Kennedy Space Center supporting the Test and Verification branch of the Constellation Ground Operations Project Office. He has over twenty five years experience in planning and performing ground testing of Space Shuttle orbiters, science payloads and experiments, and elements of the International Space Station in preparation for launch and on-orbit operations. He has extensive experience in the design and operation of aerospace emulators and simulations involved in integrated and end-to-end testing, andis currently supporting efforts to identify and specify the assets required to perform Constellation program MEIT testing at KSC. He holds a BS in Computer Engineering from the University of Florida and is obtaining his MS in Software Engineering from the Florida Institute of Technology.