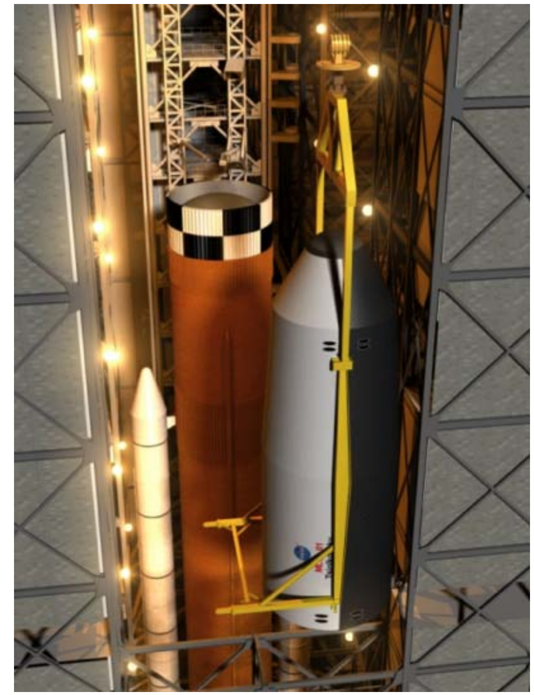
Flight Systems Integration & Test



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Logistics & Introductions

- Deactivate cells, electronics
- Housekeeping data
  - Location of restrooms and emergency exits
  - Interactive: Ask questions as we go if you like (esp. in case of acronyms/abbreviations, if necessary)
  - Breaks will last 10 minutes (however, feel free to step out briefly whenever necessary)
- Individual introductions:
  - Your name
  - Where you are from and what you do
  - One interesting and little-known fact about yourself

Workshop Overview

Topics to be Covered

- Integration and Test (I&T) Planning
- Integration and Test Flows
- Overview of Typical Mission I&T
- Supporting Elements
- Lessons-Learned and Helpful Hints
- I&T Mishaps and Failures
- The Lighter Side of I&T
- Small-Group Activity

Scope of Workshop Presentation:

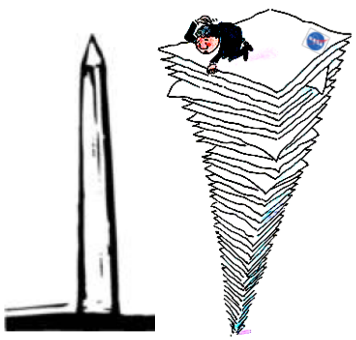
Spaceflight Payload/Observatory I&T

- Design and development not included
- Focus on hardware vs. software
- Instrument, spacecraft, observatory, and payload-vehicle I&T
- No launch site operations involving only launch vehicle
- A typical NASA "in-house" I&T program . . .

Flight Systems Integration & Test

I&T Disclaimer

- This presentation highlights a typical NASA "in-house" I&T program
  - For flight systems that are developed by NASA at a space flight center (like GSFC)
  - Requirements well-defined: qualification/acceptance, documentation, configuration mgmt.
  - Factors: precedents, human flight, risk-aversion ("failure-phobia"), taxpayer dollars, jobs
  - Some differences among NASA centers, but generally a resource-intensive process
- Typically differs from I&T performed by external organizations such as:
  - NASA contractors developing an instrument or spacecraft "bus"
  - Other government agencies
  - Commercial entities developing their own spaceflight system
- Flight systems development programs within NASA tend to be:
  - Lower risk ("failure is not an option"), taxpayer-funded
  - Less streamlined: more people, management, documentation, oversight
  - Longer timeline, more I&T "overhead"
  - Less operationally nimble: more reviews, slower response to issues
  - Higher cost



Flight Systems Integration & Test

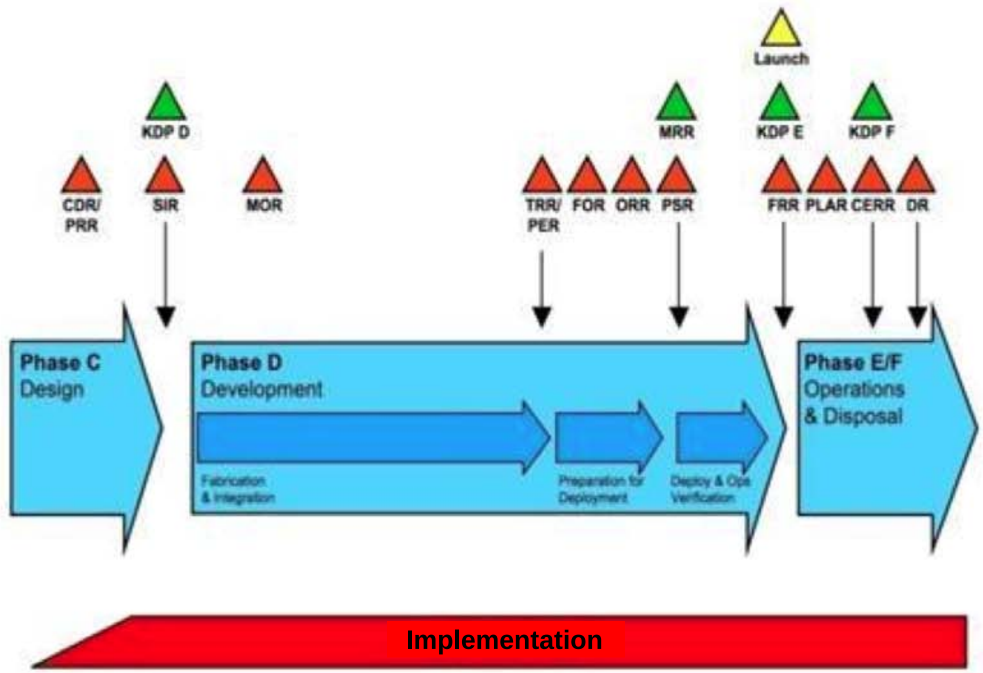
I&T Glossary

- **Integration**: The process by which flight systems or subsystems are assembled, or otherwise interconnected
- **Test**: A method of verifying that a component, element, system, or interface is functioning as specified
- **I&T**: The program by which a spaceflight system is integrated and tested in preparation for a mission
- **Validation**: Proof that a system meets needs, requirements, and specifications (i.e., "The right system was built.")
- **Verification**: Proof that an as-built system meets specific requirements and accomplishes its intended purpose (i.e., "The system was built right.")
- **Subsystem**: A discipline-specific support system (e.g., structures, electrical, propulsion) that is integrated with other subsystems to make up an instrument, spacecraft bus, observatory (or payload), or vehicle
- **Instrument:** Customer experiment hardware that is integrated with a spacecraft (or carrier) to make a payload
- **Payload**: Integrated observatory or carrier/instrument complement that is integrated with a launch vehicle
- **Bus**: The integrated subsystems that comprise a spacecraft (structure, power, data, comm., prop, etc.)
- **Observatory**: The integrated payload, usually a satellite or probe, comprised of a bus and instruments
- **Carrier**: The flight system that accommodates instruments or multiple payloads, often synonymous with "bus"
- **Vehicle**: The launch vehicle used to deliver payloads or other hardware into space
- **Element**: A part of the overall spaceflight system, such as a subsystem assembly, payload, vehicle, module, lander, or ground system.
- **Interface**: A physical interconnecting boundary between components, subsystems, or elements; may refer to structural, electrical, thermal, or other hardware interface; usually defined in an interface control document (ICD)
- **Environmental:** A phase of testing that subjects hardware to simulated spaceflight conditions
- **Ground Support Equipment (GSE)**: Any nonflight equipment used to support the flight system prior to launch; can be discipline-specific (MGSE, EGSE); may be used to support mission operations (e.g., command, telemetry)
- **Configuration Management (CM):** The process that ensures the as-built state of an element or system (including GSE and software) is maintained, and that any modifications, open issues, or actions taken are tracked

Flight Systems Integration & Test

Project Life-Cycle

Implementation Phases



Phase C
- " Design the system right"
- Complete the detailed system design,
- Drawings complete
- CDR: Review drawings and test plans
- SIR: System Integration Review

Phase D
- Build, integrate, verify, launch the system, and prepare for operations
- MOR: Mission Operations Review
- FOR: Flight Operations Review
- TRR: Test Readiness
- PER: Pre-Environmental Readiness
- Verification & Preparation for deployment
- PSR: Pres-Ship Readiness
- FRR: Flight Readiness
- Deployment and operations verification
- ORR: Operational Readiness

Phase E/F
- Operate the system and dispose of it properly
- PLAR: Post-Launch Assessment Review
- CERR: Critical Events Readiness Review
- DR: Disposal Review

Integration Phases or Levels

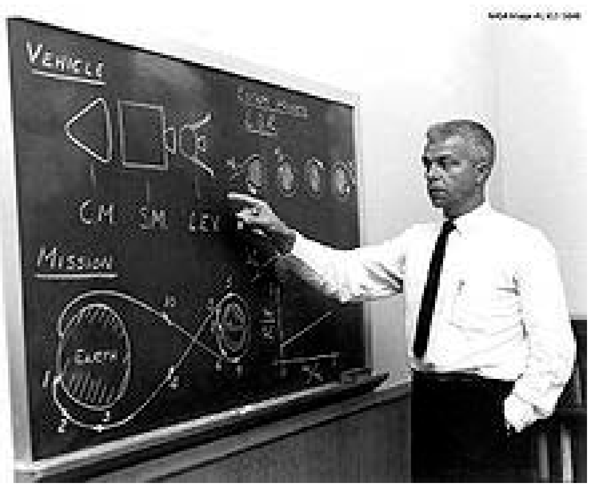
Subsystem
or Instrument

Spacecraft
Bus

Observatory
or Payload

Launch
Vehicle

Integration and Test Planning:
Preparing to Get the Job Done



The I&T Team
People That Make It Happen

- I&T manager and engineers
- Systems engineers
- Subsystem/discipline engineers and technicians
  - Command and data handling (C&DH)
  - Electrical/power
  - Mechanical
  - Thermal
  - Propulsion (prop)
  - Alignment
  - Optics
  - Instruments
  - Communications (comm)
  - Materials, parts
  - Contamination control
  - Flight software (FSW)
  - GSE (mechanical, electrical)
  - Attitude control system (ACS) or guidance, navigation, & control (GNC)

- Test conductors (including flight operations team)
- Safety and mission assurance
- Facilities (cleanroom, environmental, etc.)
- Configuration management (CM)
- Shipping, logistics

The I&T Manager:

Foreman, Shepherd, Coach_

- Develops I&T plans and schedules
  - Based on project design and system verification requirement
  - May start as early as Phase A proposal
  - Develops realistic schedule and resource estimates

- Coordinates resources needed for I&T
  - Personnel, training
  - Equipment, procurements
  - Facilities, infrastructure
- Organizes and leads I&T team in day-to-day I&T activities
  - Keeps team informed, motivated
  - Addresses any I&T issues that may arise
- Facilitates I&T process - keeps things moving
  - Effectively uses time, e.g., even when scheduled tasks are delay
  - Ensures tasks completed on schedule, barring unforeseen circumstances
- Jack (or Jill) of all trades
  - Broad understanding of various engineering disciplines
  - Familiar with flight and ground systems
  - Helps project make progress despite potential setbacks

I&T Team Roles & Responsibilities

- Systems engineers
  - Develop verification requirements, integrated test plans and procedures
  - Support I&T activities and verifies requirements are met
- Subsystem/discipline engineers and technicians
  - Develop/deliver subsystem assemblies, subsystem I&T plans and procedures
  - Perform/support subsystem I&T with spacecraft and observatory
- Test conductors (TC's)
  - Develop ground system displays and scripts for S/C control & monitoring
  - S/C operators during testing, for command/monitoring of flight systems
  - Typically include the Flight Operations Team (FOT)
- Safety and mission assurance
  - Provides safety and quality control oversight, problem/failure tracking
  - Supports/monitors I&T operations as needed
- Facilities
  - Provides facilities and infrastructure (e.g., cranes, power) required for I&T
  - Ensures contamination control requirements are met
- Other support services
  - Configuration management for documentation approvals and support
  - Shipping and logistics for flight hardware and ground support equipment

Unofficial Team Roles

© PNTS

- The Visionary
  - Sees the path forward
- The Counselor
  - Listens to problems and helps resolve them
- The Straight Shooter
  - Tells management when things could be better
- The Housekeeper
  - Dots the I's and crosses the T's
- The Head Cheerleader
  - Gives out recognition; team-builder
- The Class Clown
  - Keeps the atmosphere light and fun
- The Magician
  - Knows how to get things done inside or outside system

Flight Hardware Test Definitions

- Design qualification testing
  - Demonstrates that hardware will function within performance specifications under simulated conditions more severe than those expected from ground handling, launch, and mission ops
  - Purpose is to uncover deficiencies in design and method of manufacture
  - Not intended to exceed design safety margins or to introduce unrealistic failure modes
  - Two approaches to qualification testing: prototype and protoflight
- Prototype vs. protoflight
  - Prototype: Utilizes non-flight hardware as surrogate for flight hardware during qualification tests
  - Protoflight: Tests flight hardware to qualification test levels and acceptance test durations
  - Choice depends on factors like hardware availability, budget, accepted risk, schedule, etc.
- Flight acceptance testing
  - Verification process that demonstrates hardware is acceptable for flight
  - Assumes that design qualification testing has been successfully performed
  - Serves as a quality control screen to detect deficiencies, e.g., workmanship
  - Can provide basis for delivery of a flight item under terms of a contract
  - Less rigorous test levels than those for qualification testing
- Workmanship testing
  - Environmental tests performed to verify proper construction or assembly of flight hardware
  - Hardware subjected to stresses beyond those predicted for flight, in order to uncover defects
  - Includes random vibration and thermal-vacuum cycling

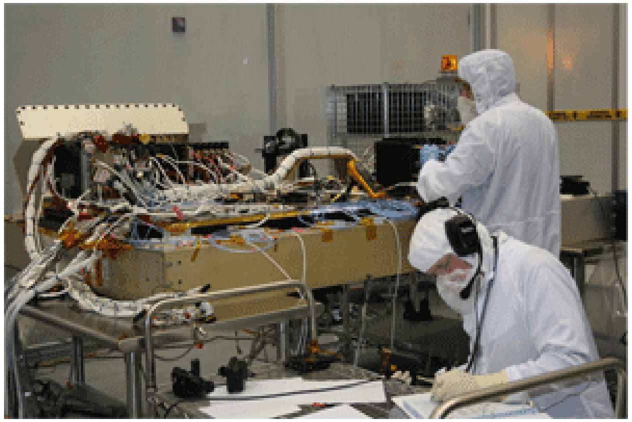
Flight Systems Integration & Test

I&T Facility Considerations

- Size
  - Area, height (incl. crane hook-height)
  - Cleanliness level (per ISO-14644-1)
  - Floor space for EGSE, MGSE, TC workstations
- Infrastructure and services
  - Cranes, lifts
  - Power, grounding
  - Networks (internet, phone, intercomm)
  - Environmental control (temp, humidity, cleanliness)
- Logistics
  - Proximity to subsystem, instrument, bus development
  - Proximity to truck docks/locks
  - Office space and equipment (printers, copiers)
  - Bonded storage space
- Scheduling
  - Among other projects, potential conflicts
  - Modifications required for project
  - Planned outtages

Plans and Procedures

- Purpose
  - To ensure I&T approach and tasks are defined in advance
  - To allow proper review and approval by those involved
  - To ensure adequate resources to get the job done
- Plans - examples
  - Integration and Test
  - Contamination Control
  - Safety
  - Transport



- Procedures - examples
  - Subsystem integration
  - Observatory thermal-vacuum test
  - Comprehensive performance test
  - Prelaunch closeouts
- Procedures should cover any hazards
  - Identified as hazardous; approved by safety
  - Emergency instructions included at end
- Review, approve, release
  - Completed far enough in advance to allow proper review and edits
  - Completed in time for team to become familiar and complete preparations

Flight Systems Integration & Test

Verification Test Matrix

HARDWARE DESCRIPTION					
LEVEL OF ASSEMBLY	ITEM	S/N	UNIT TYPE	SUPPLIER	QUALIFICATION STATUS

STRUCTURAL MECHANICAL												
MODAL SURVEY	STATIC LOADS	ACCELERATION	SINE BURST	SINE VIBRATION	RANDOM VIBRATION	ACOUSTICS	MECHANICAL SHOCK	PRESSURE PROFILE	MECHANICAL FUNCTION	TORQUE RATIO	LIFE TESTS	MASS PROPERTIES

EMC & MAGNETICS																					
EMISSIONS									SUSCEPTIBILITY												
CONDUCTED						RADIATED			CONDUCTED								RADIATED				
DC POWER LEADS	AC POWER LEADS	POWER LEADS	SPIKES ON ORBITER DC POWER LINES	SPIKES ON ORBITER AC POWER LINES	ANTENNA TERMINALS	MAGNETIC FIELD (STS PAYLOADS)	AC MAGNETIC FIELD	E-FIELDS	PAYLOAD TRANSMITTERS	SPURIOUS (XMTR ANTENNA)	POWER LINE	INTERMODULATION PRODUCTS	SIGNAL REJECTION	CROSS MODULATION	POWER LINE TRANSIENTS	E-FIELD (GENERAL COMPATIBILITY)	COMPATIBILITY WITH ORBITER XMTR'S	ORBITER UNINTENTIONAL E-FIELD	MAGNETIC-FIELD SUSCEPTIBILITY	MAGNETIC PROPERTIES	

THERMAL								
LEAK	NUMBER OF THERMAL-VACUUM CYCLES	NO. OF THERMAL CYCLES (NON-VAC)	THERMAL BALANCE	TEMPERATURE-HUMIDITY	BAKEOUT	FLIGHT TEMPERATURE PREDICTIONS	TEST TEMPERATURE LIMITS	REMARKS

LEGEND

LEVEL OF ASSEMBLY

- S/C - SPACECRAFT
- P/L - PAYLOAD
- MOD - MODULE
- S - SUBSYSTEM
- I - INSTRUMENT
- SEC - SECTION
- C - COMPONENT

UNIT TYPE

- D - DEVELOPMENT MODEL
- EM - ENGINEERING MODEL
- PT - PROTOTYPE
- PF - PROTOFLIGHT
- F - FLIGHT
- S - SPARE

QUALIFICATION STATUS

1. - COMPLETE QUAL. REQUIRED
2. - PARTIAL QUAL. REQUIRED (SEE REMARKS)
3. - OTHERWISE QUALIFIED (SEE REMARKS)

NOTES:

I&T Preparations

Months in Advance

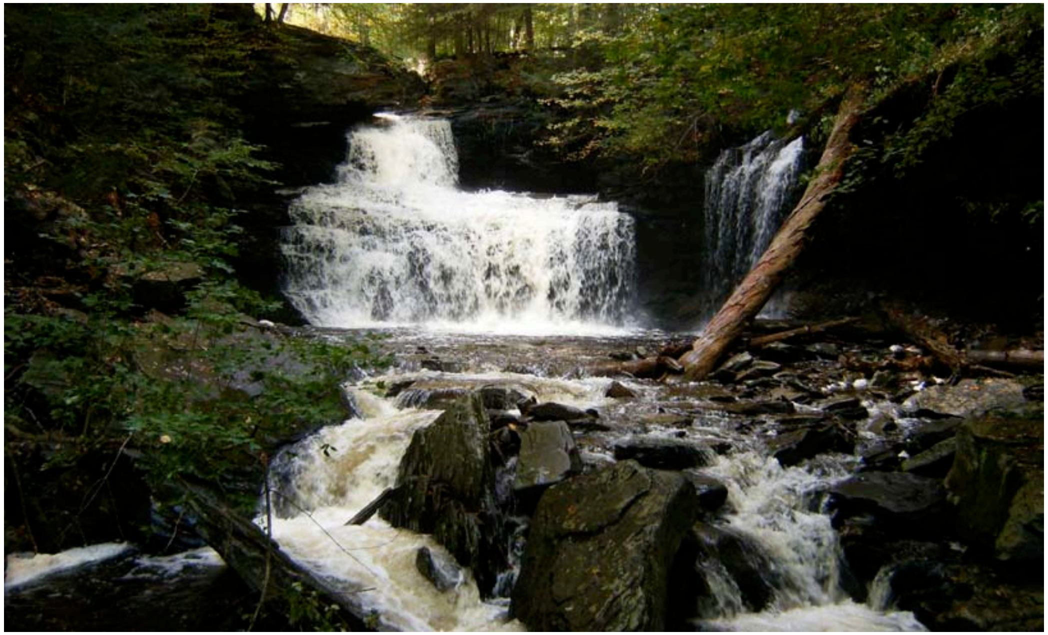
- I&T peer review
  - Independent review of I&T plans
  - Usually prior to major design review (e.g., PDR, CDR)
- Facilities
  - Cleanroom certification
  - Electrostatic Discharge (ESD) certification of benches
  - Bonded storage area
  - Security, as necessary
  - Scheduling: among other projects, any modifications required
- Team training
  - Project and flight system familiarization
  - Certifications (e.g., ESD, cleanroom, crane, fab, mate/demate)
  - Ground test system (TC's)
- Ground support equipment (GSE)
  - COTS equipment procurement
  - Unique GSE fabrication
  - EGSE calibration
  - MGSE load testing
- Procedure development
  - Review, approve, release well in advance of need date

Flight Systems Integration & Test

I&T Operations Protocol

- Pretask briefing
  - Go over procedure with team
  - Roles of each participant, identification of alternates (if needed)
  - Review any safety hazards and emergency instructions
  - Conduct hardware walk-down to verify pretask configuration
- Procedures
  - Required for any operations involving flight systems (and sometimes GSE)
  - Any deviations must be coordinated with engineers and approved
  - Redlines noted on as-run copy
- Maintain configuration
  - Applies to both flight and ground system, hardware and software (e.g, GLO-1)
  - Current hardware/software configuration should be known at any given time
  - When a problem arises, freeze (unless safing required); assess, document, and consult with engineers before proceeding
- Task performance
  - Task led by task leader
  - Control and monitoring of spacecraft by TC's
  - Area around hardware restricted to those actively supporting task
  - Maintain task/test team discipline, organized work area
  - Anyone can call a stop to work if safety hazard is observed
- Avoid concurrent tasks
  - Especially if spacecraft is powered (although there have been exceptions)
  - Focus on primary task, with last-minute "walk-ons" scheduled as time permits

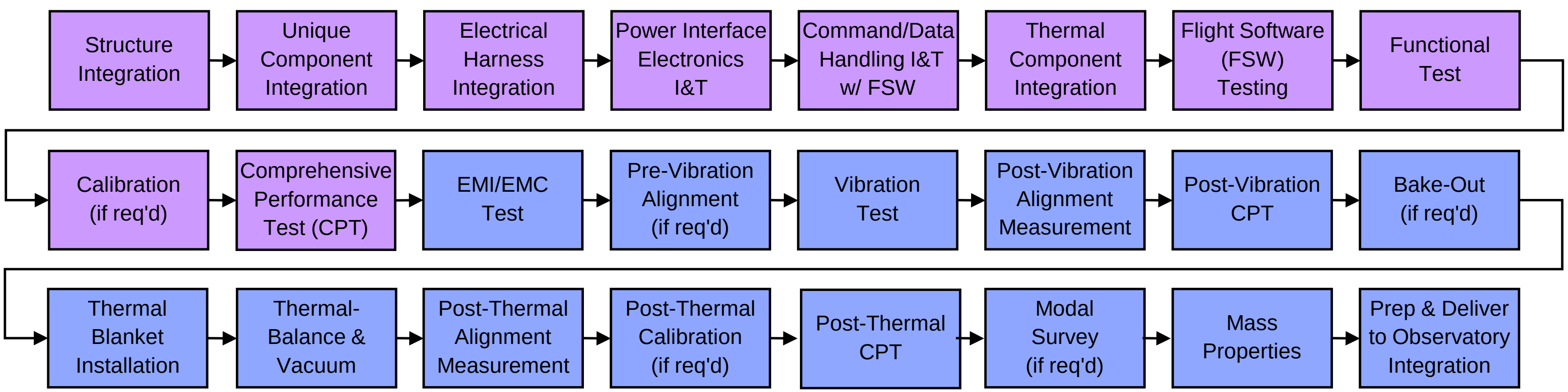
Integration and Test Flows:
Simple Graphical Representations of Rather Complex Processes



Subsystem or Instrument I&T

- Includes tasks necessary for subsystem- or instrument-level I&T
  - Subsystem components: mechanical, electrical, thermal, unique (e.g., detector)
  - Functional and comprehensive performance tests (CPT's)
  - Subsystem- or instrument-specific tests (calibration, characterization, etc.)
- Environmental qualification testing
  - Electromagnetic interference/compatibility (EMI/EMC): radiated, conducted
  - Three-axis vibration: workmanship, random, sine-sweep
  - Thermal: balance, vacuum

Representative Subsystem/Instrument I&T Flow



Notes: - "I&T" includes: mechanical integration, electrical safe-to-mates, and/or functional testing
- Short functional tests performed following each vibration (axis) test
- Task sequence for reference only; some tasks may be performed in parallel (e.g., harness, thermal h/w)

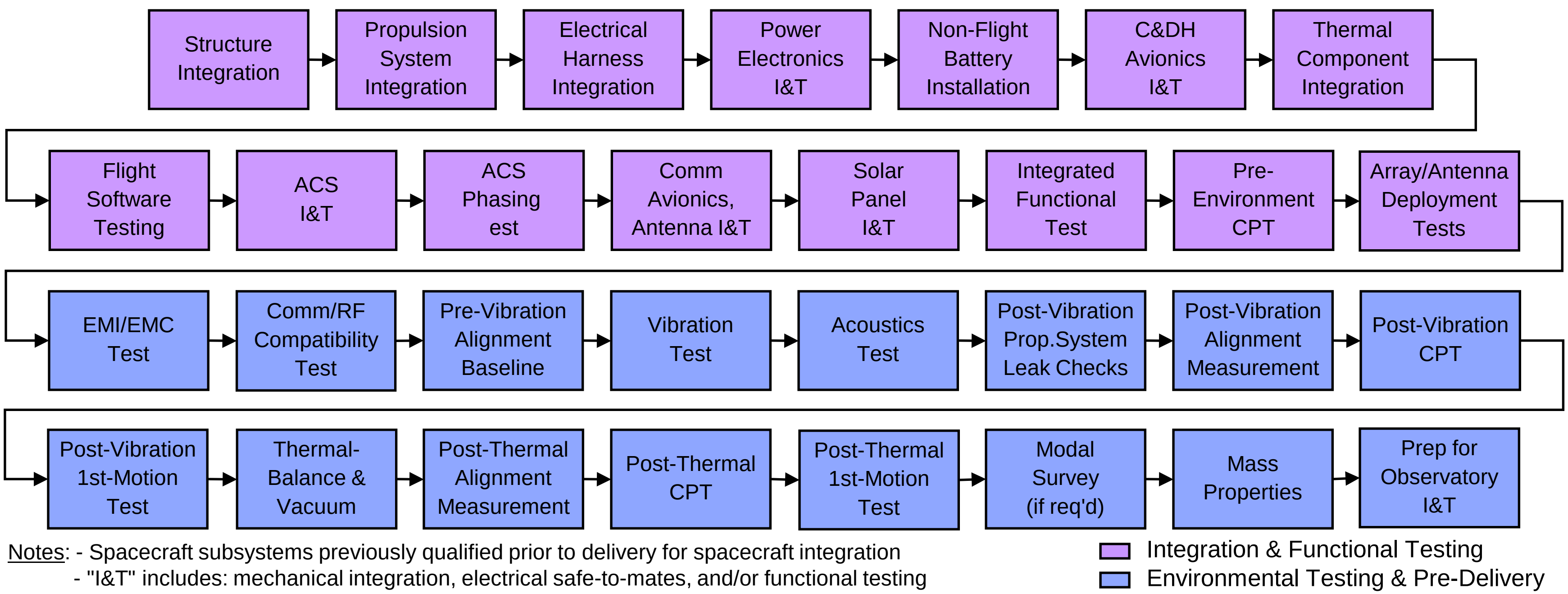
Integration & functional testing
Environmental testing, pre-delivery

Flight Systems Integration & Test

Spacecraft Bus I&T

- Includes tasks necessary for spacecraft-level I&T
  - Subsystems: structures/mechanical, power, C&DH, thermal, ACS, prop, comm, FSW
  - Functional and comprehensive performance tests (CPT's)
- Environmental qualification testing
  - Electrical/Comm: EMI/EMC, radio-frequency (RF) compatibility test
  - Mechanical: random vibration, sine-sweep, acoustics, shock, modal survey (if req'd)
  - Thermal: balance, vacuum

Representative Spacecraft Bus I&T Flow



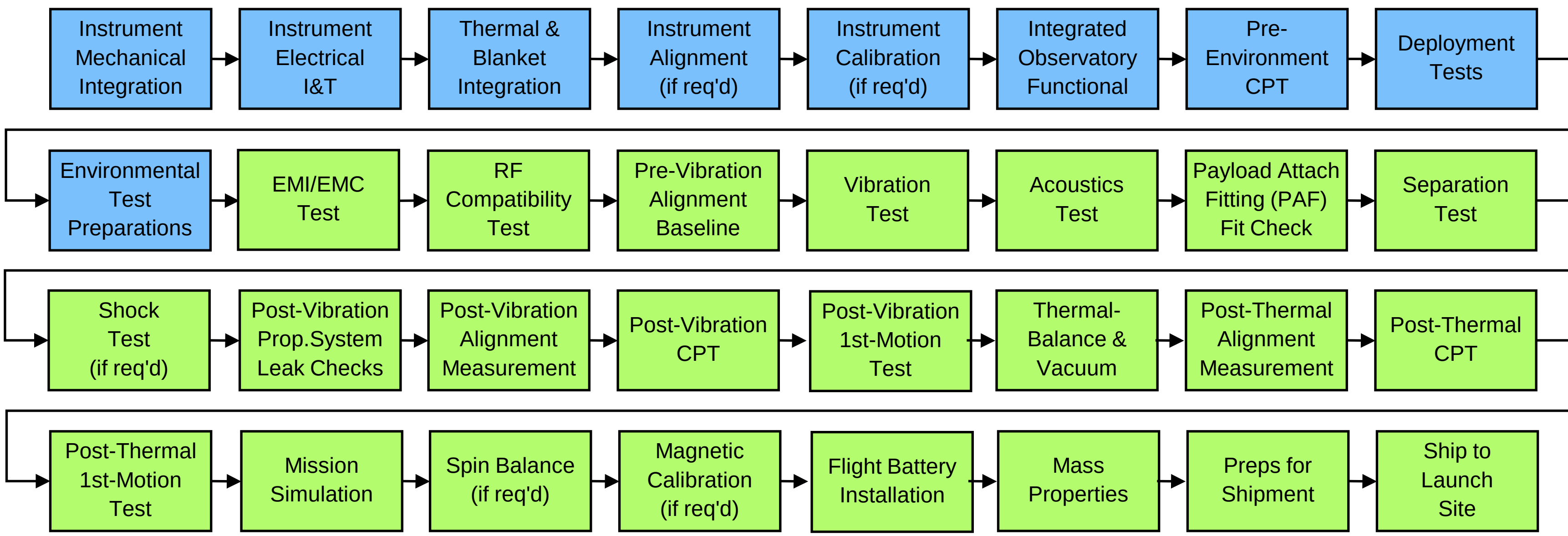
Notes: - Spacecraft subsystems previously qualified prior to delivery for spacecraft integration
- "I&T" includes: mechanical integration, electrical safe-to-mates, and/or functional testing
- Short functional test performed following each vibration (axis) test
- Task sequence for reference only; some tasks may be performed in parallel (e.g., harness, thermal h/w)

Flight Systems Integration & Test

Observatory or Payload I&T

- Includes tasks necessary for integrated observatory/payload I&T
  - Integration of instruments (single or multiple), typically sequentially
  - Functional and comprehensive performance tests (CPT's)
  - All other operations required to be completed prior to delivery to launch site
- Environmental qualification testing
  - Electrical/Comm: EMI/EMC, RF compatibility test
  - Mechanical: random vibration, sine-sweep, acoustics, shock, modal survey (if req'd)
  - Thermal: balance, vacuum

Representative Observatory/Payload I&T Flow



Notes: - Spacecraft bus & instruments previously qualified prior to delivery for observatory integration
- "I&T" includes: mechanical integration, electrical safe-to-mates, and/or functional testing
- Short functional test performed following each vibration (axis) test
- Task sequence for reference only; some tasks may be performed in parallel (e.g., harness, thermal h/w)

Integration & Functional Testing
Environmental Testing & Predelivery

Some Instrument-Unique Requirements

- Contamination control
  - Purges: nitrogen, clean air, etc.
  - Dry-Heat Microbial Reduction for planetary protection (e.g., some SAM components vacuum-baked at 752° F/400 C)
- Calibration and characterization
  - Optical (typ. for telescopes)
  - Laser (e.g., LOLA)
  - Video (e.g., MEIDEX)
  - Radioactive source (e.g., LEND)
  - Magnetic calibration (typ. for magnetometers)
- Alignment
  - Absolute (e.g., GNC components)
  - Relative measurement ("knowledge-only")
- Special handling
  - Orientation (e.g., CAPL)
  - Vibration (e.g., CVX-2)
  - Hazards

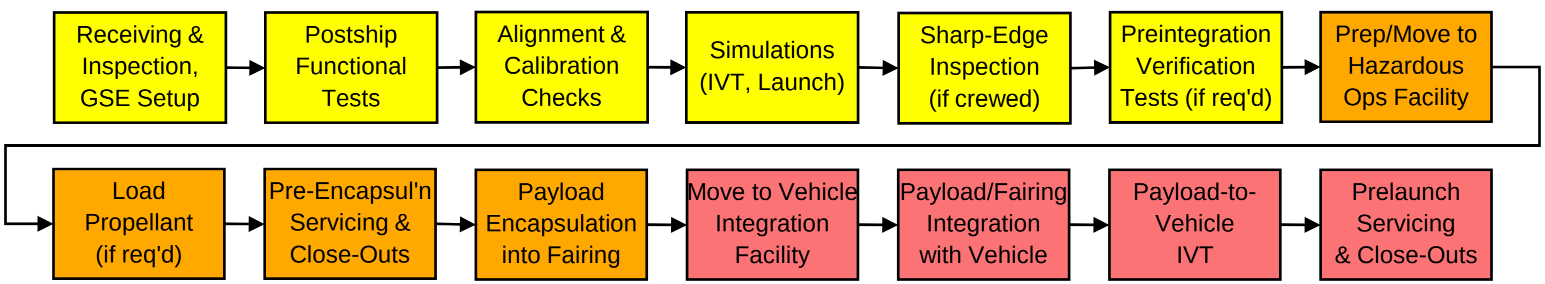
Differences for Follow-On Hardware

- Applies to hardware reflown or fabricated using previously flown design
- Environmental would include acceptance testing only
  - However, any design mods may require qualification testing
- Limited integrated environmental testing
  - EMI/EMC
  - Workmanship vibration
  - Thermal-vacuum to acceptance test levels
- Benefit of previous I&T experience, lessons learned
  - Reuse of existing drawings, procedures, GSE, etc.
  - Incorporation of enhancements to processes, GSE (e.g., displays)
  - Know what to expect, few if any "surprises"
  - If same team, no new training required (recertification may be necessary)
  - Shorter overall I&T timeline

Launch Site Operations

- Includes payload post-delivery tasks and integration with launch vehicle
  - Postship functional testing
  - Integration of any "late" hardware following payload delivery to launch site
  - Last-minute servicing, fueling, and close-outs prior to vehicle integration
  - Vehicle integration and interface verification test (IVT)
  - Late-access operations at vehicle integration facility (I&T, servicing, closeouts)
- All hardware fully qualified and tested prior to delivery
  - No environmental testing at launch site
  - Some preintegration verification may be req'd (e.g., CITE, MEIT)

Representative Launch Site Operations Flow



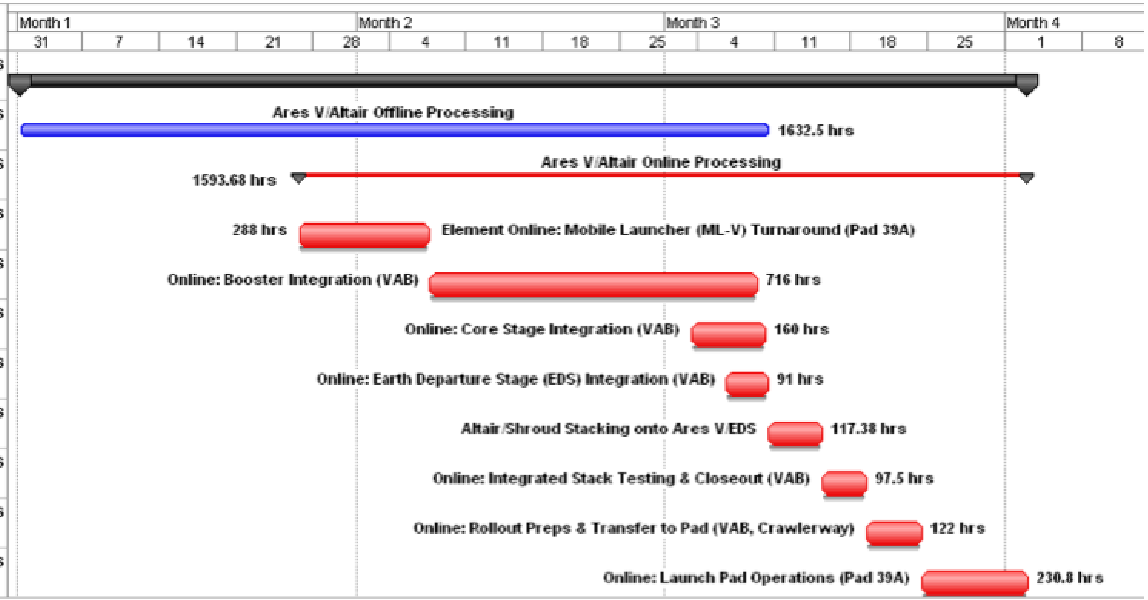
Notes: - Co-manifested payload operations not shown
- Some tasks may not be contiguous, i.e., due to launch site scheduling or vehicle operations
- Servicing may include purging, top-charging, arming, cover removal, or instrument-unique tasks
- Task sequence for reference only; some tasks may be performed in parallel (e.g., payload functionals)

Payload Offline Processing Operations
Hazardous Processing Facility Operations
Integrated Vehicle & Pad Operations

Vehicle Integration Timeline

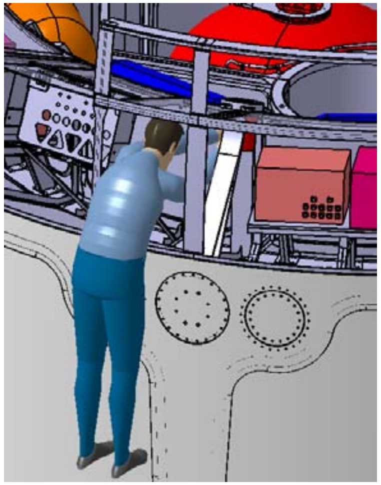
- Includes major integrated operations required prior to launch
- Payload integration on order of weeks or days before launch
- Prelaunch operations start L-days
- All operations controlled by launch site and vehicle organizations

ID	Task Name	Duration
1	Ares V/Altair Integrated Ground Operations Timeline(KSC)	2200.18 hrs
2	Ares V/Altair Offline Processing	1632.5 hrs
478	Ares V/Altair Online Processing	1593.68 hrs
479	Element Online: Mobile Launcher (ML-V) Turnaround (Pad 39A)	288 hrs
503	Online: Booster Integration (VAB)	716 hrs
600	Online: Core Stage Integration (VAB)	160 hrs
626	Online: Earth Departure Stage (EDS) Integration (VAB)	91 hrs
652	Altair/Shroud Stacking onto Ares V/EDS	117.38 hrs
680	Online: Integrated Stack Testing & Closeout (VAB)	97.5 hrs
707	Online: Rollout Preps & Transfer to Pad (VAB, Crawlerway)	122 hrs
717	Online: Launch Pad Operations (Pad 39A)	230.8 hrs



Late Pad Access Payload Operations

- Considered "late" since follows typical payload integration
  - Performed at launch pad or other vehicle integration facility
  - Requires unique resources and is usually serial impact to vehicle schedule
  - Typically performed days or hours before launch
  - Since occurs after key integrated tests, introduces risk to mission success
  - Hardware interfaces and procedures validated via fit-checks and simulations
- Tasks requiring late access:
  - Instrument delivery following payload integration into vehicle
  - Last-minute manifesting of hardware (e.g., ISS replacement)
  - Time-critical installations (e.g., living specimens)
  - Preplanned payload tasks: purges, trickle-charging, arming, red/green tags



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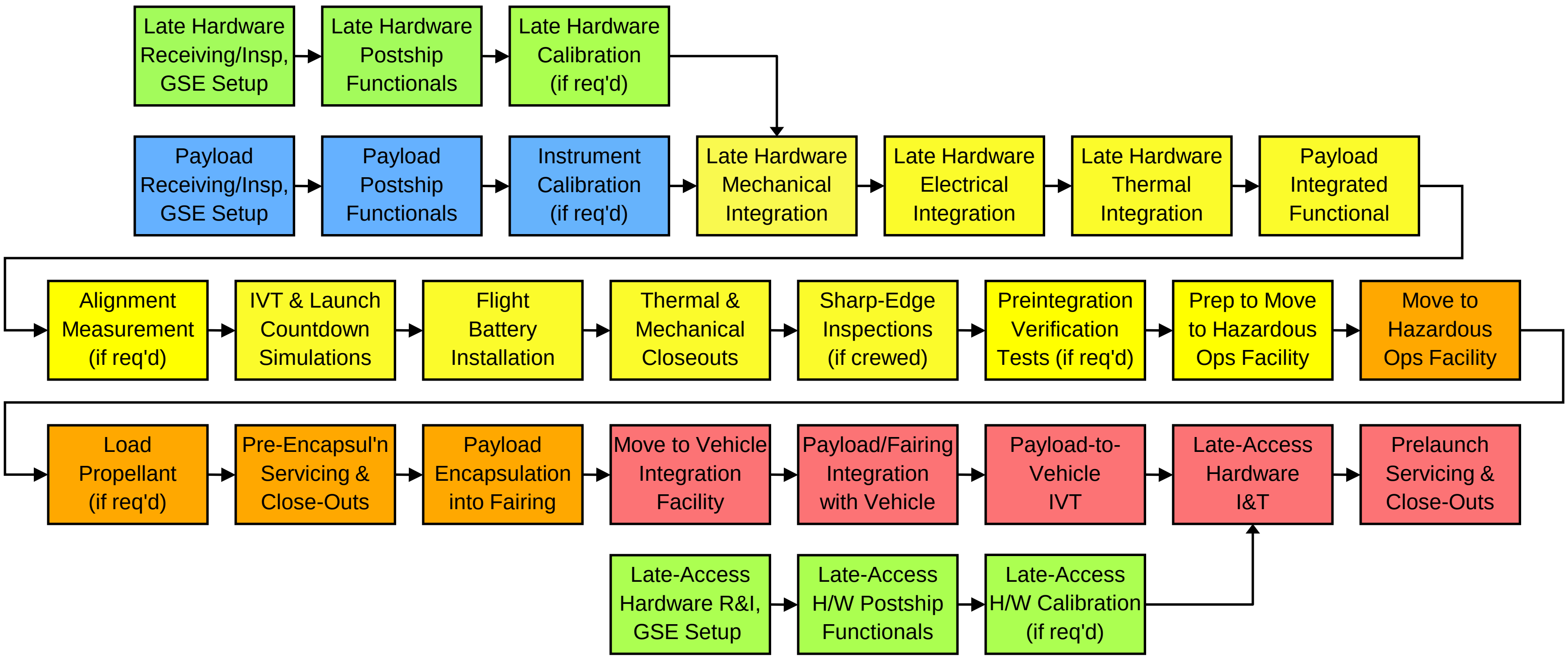
Launch Site Operations
for Late Hardware Deliveries



Notes: - Some tasks may not be contiguous, i.e., due to launch site scheduling or vehicle operations
- Task sequence for reference only; some tasks may be performed in parallel (e.g., payload functionals)
- Servicing may include purging, top-charging, arming, cover removal, or instrument-unique tasks

- Preintegrated Payload Offline Operations
- Late & Late-Access H/W Offline Operations
- Integrated Payload Offline Operations
- Hazardous Processing Facility Operations
- Integrated Vehicle & Pad Operations

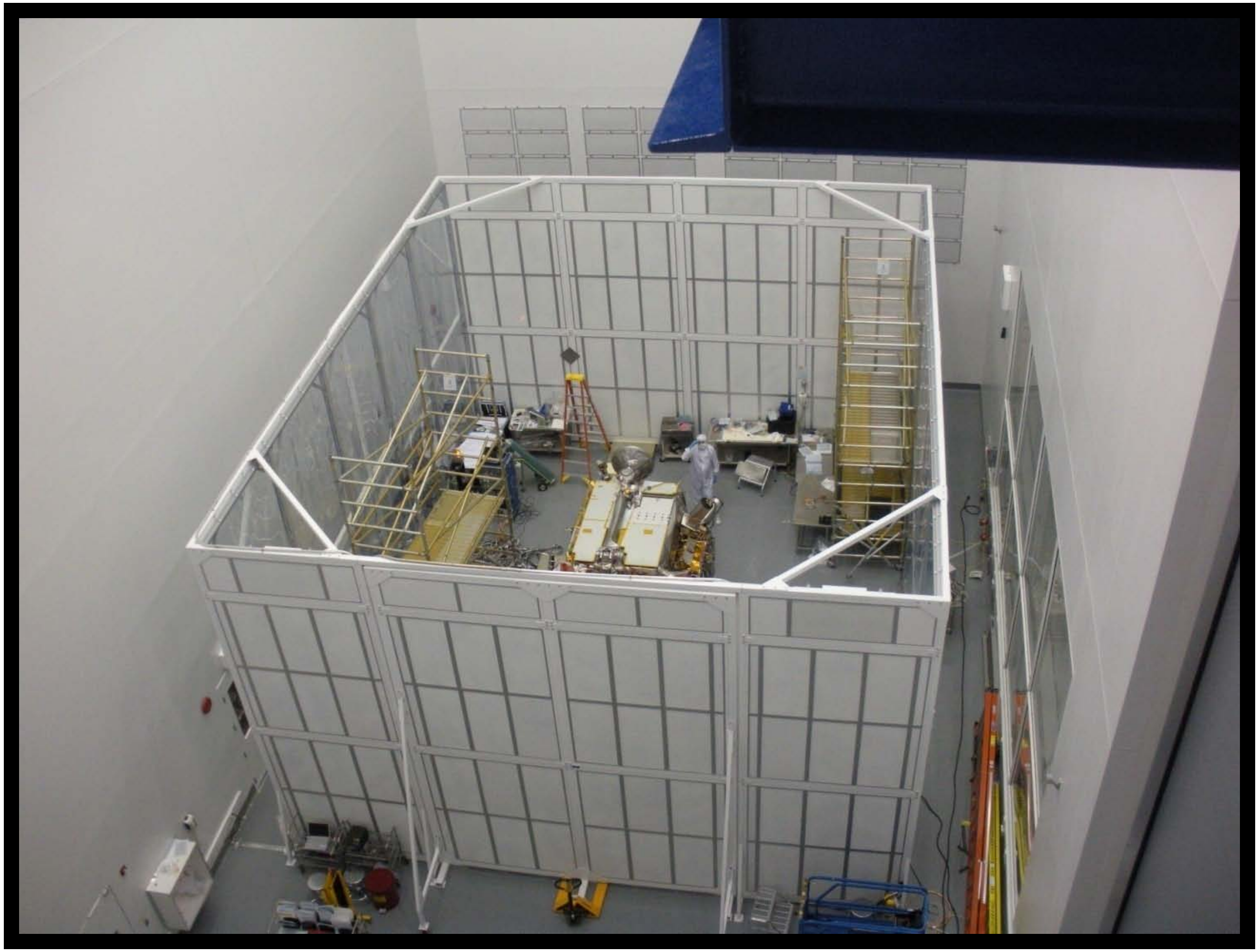
Overview of Typical Mission I&T:

Lunar Reconnaissance Orbiter
Integration and Test

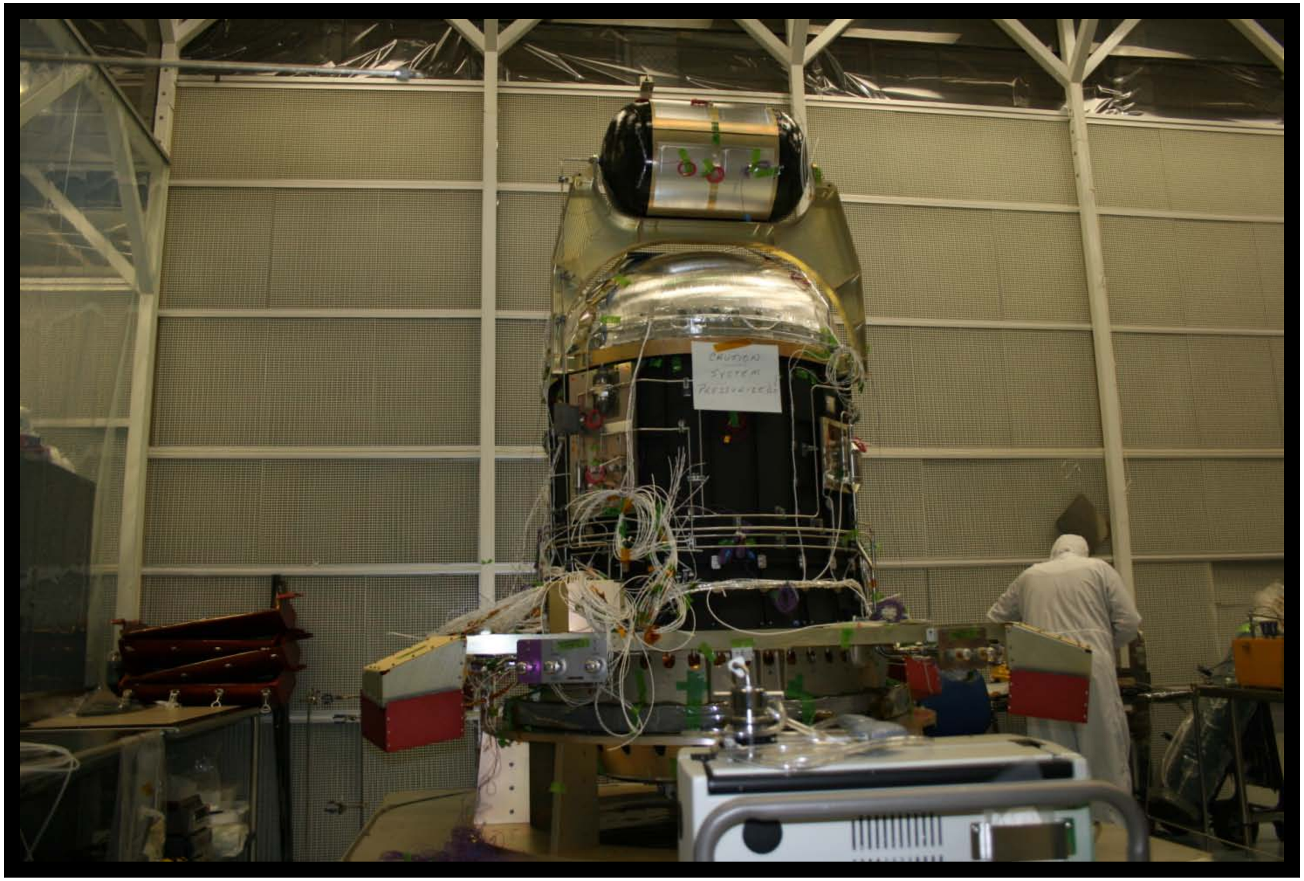
Flight Systems Integration & Test

The LRO Clean Room

a.k.a. "The White House"

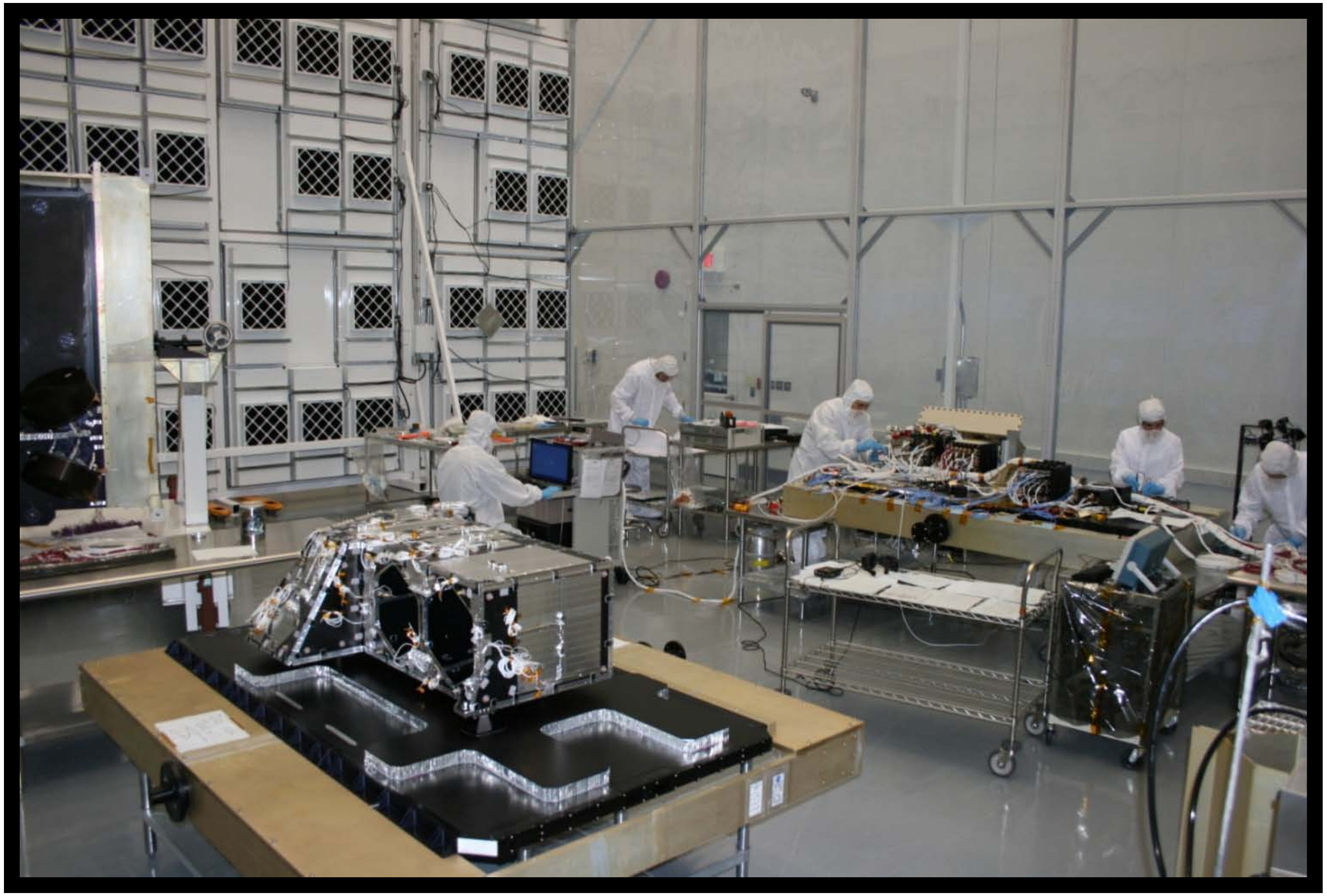


Propulsion System Integration



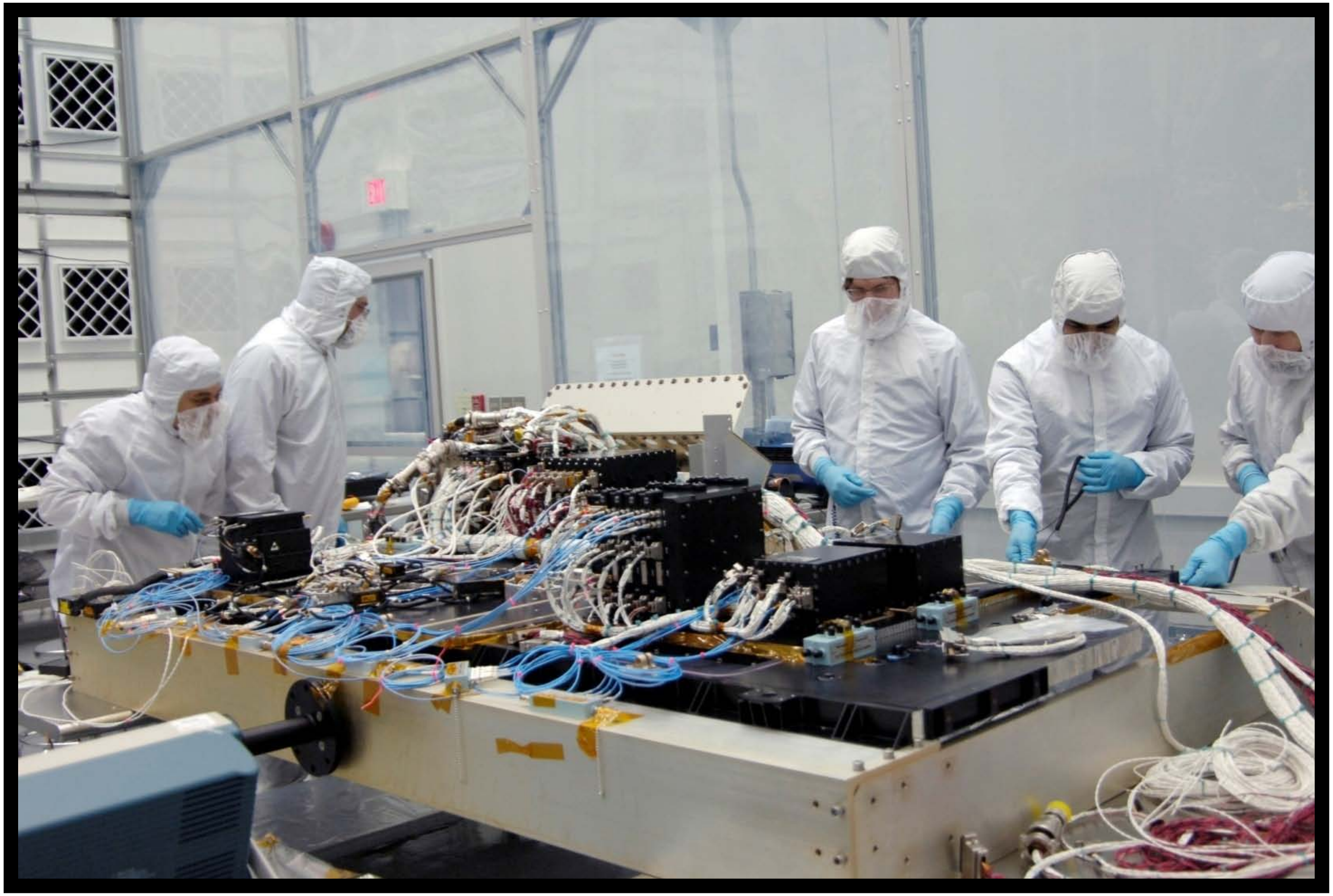
Flight Systems Integration & Test

Avionics, Instrument, and Reaction Wheel Module Integration



Flight Systems Integration & Test

Avionics Module

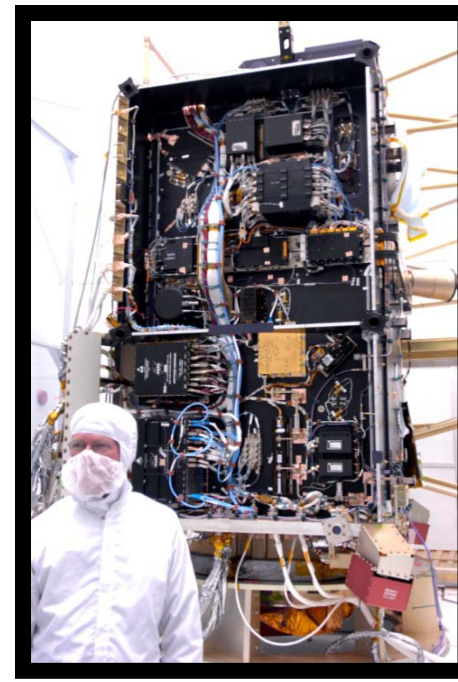


Flight Systems Integration & Test

Spacecraft Bus Modules

+Y Panel with Optical Bench

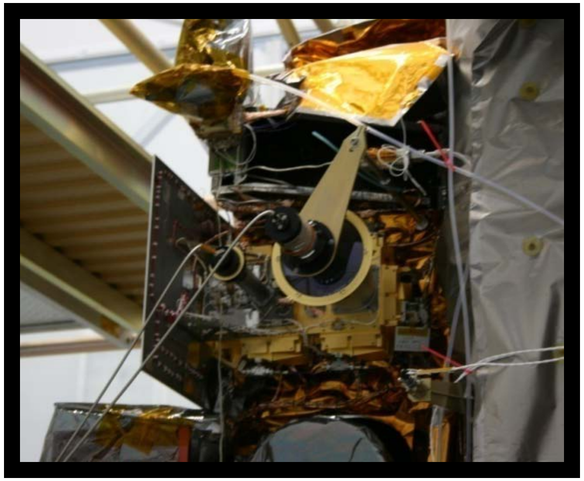
Propulsion Module with –Z ; -Y; +X Panels

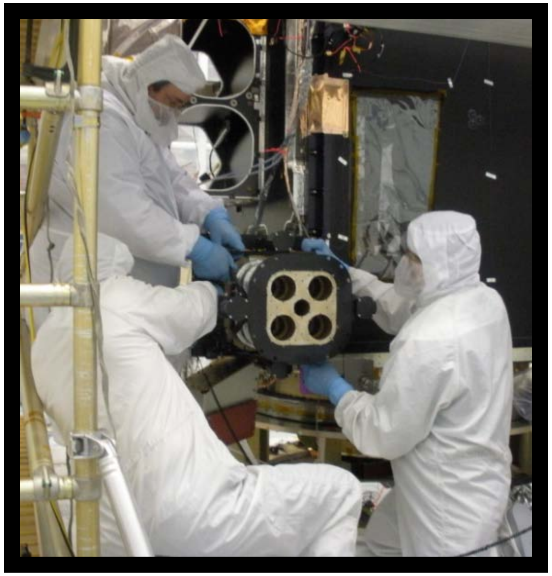


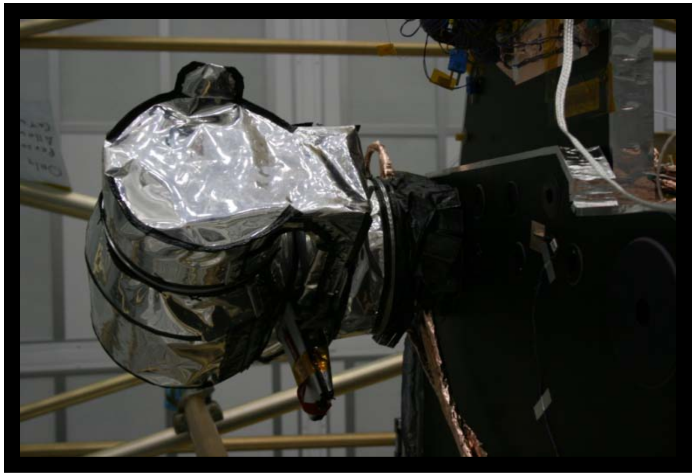
-Y Panel with Avionics

Flight Systems Integration & Test

Instrument Integration

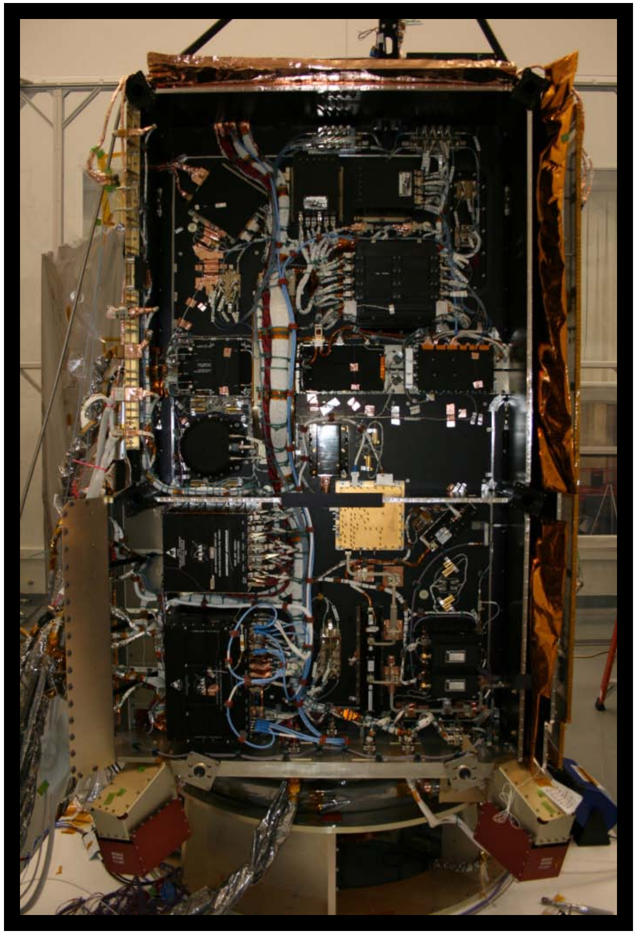






Flight Systems Integration & Test

Orbiter Integration



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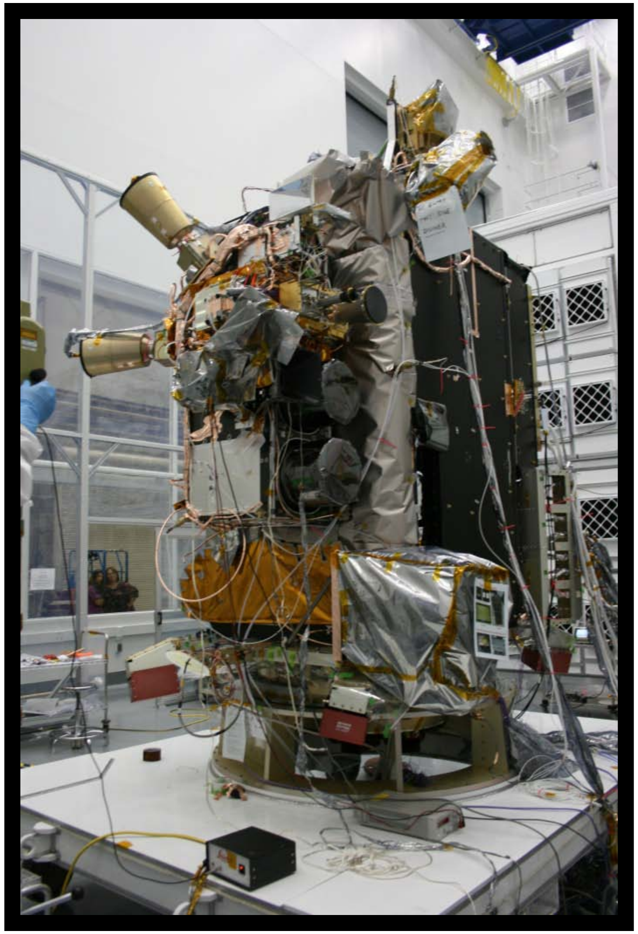

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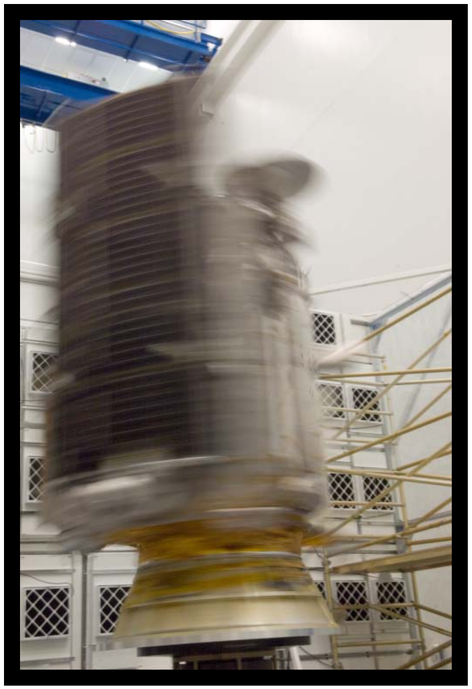
Flight Systems Integration & Test

Orbiter Level Testing

Mechanical Environmental Testing



Mass Properties

Vibration

Acoustics

Flight Systems Integration & Test

Electromagnetic Compatibility Testing

Flight Systems Integration & Test

Thermal Vacuum Test

Shipping to the Launch Site

Flight Systems Integration & Test

Encapsulation

Flight Systems Integration & Test

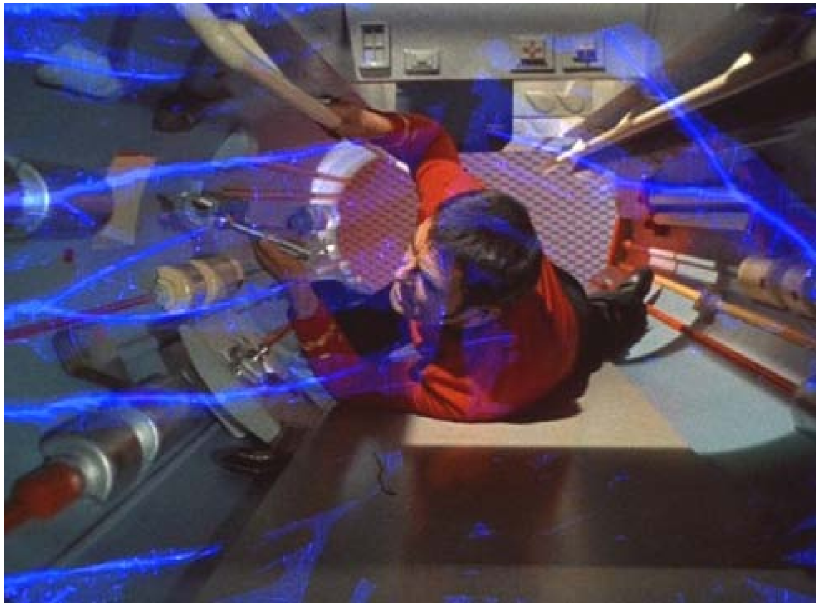
Stacking onto Launch Vehicle

Flight Systems Integration & Test

Launch

Atlas-V

Supporting Elements:
Tools to Get the Job Done



Ground Support Equipment (GSE)

- Subsystem GSE (typical)
  - Mechanical: tools, dollies, purge carts, scaffolding
  - Electrical: meters, o'scopes, break-out boxes, power supplies
  - Thermal: shrouds, thermocouples
  - Comm: hat couplers, compatibility test van, networks
  - Optical: scopes, lasers, calibrators, integrating spheres
  - Facility: cranes, power, clean tents
- Ground test system
  - Commanding, telemetry monitoring
  - Flight software upload
  - Usually operated by qualified TC's
- Flatsats and simulators
  - From rudimentary breadboards to flight-like Engineering Test Units (ETU's)
  - From bench-level to full-size mockups (e.g., crew module)
  - Used for software validation, preintegration testing, training
  - Requires some level of validation prior to commissioning
- All GSE designed to meet most stringent requirements
  - Contamination control: materials, wheel covers, lubricants
  - Safety: fire-retardant paint, electrical shock, sharp edges, tip-over analysis
  - Protection of interfaces to flight hardware (e.g., grounding, over-current)

CM & Process Documentation

- Procedures
  - Covers planned activities, hazards
  - Usually fulfill predefined requirements
  - Written in advance w/ semi-formal review/approval process
- Work authorizations
  - Covers planned and unplanned activities
  - Usually for short tasks that do not involve extensive resources
  - Less rigorous review process
- Logs
  - Operational logs (e.g., TC, mate/demate, run time, etc.)
  - Certification logs (typically tied to specific flight hardware items)
- Configuration change requests
  - For hardware and software modifications (e.g, UVSTAR)
  - Requires approval by predefined "change board"
  - Enables tracking changes to help maintain record of current configuration
- Problem and "mishap" reporting
  - Tracks major and minor anomalies and unexpected occurances
  - Includes hardware and software problems and any accidents/incidents
  - Usually requires approval of repair/replacement prior to any action taken
  - Alternative is to accept problem or condition as-is for flight (w/ approvals)

Transportation to Launch Site

- Planning considerations
  - Distance from integration facility
  - Mode of transport (air, rail, truck, ship)
  - Dimensions of transport with container (e.g., height if via truck)
- Pre-planning
  - Logistics coordination
  - Container design: size, int/ext. cleanliness, environmental control
  - Loading/offloading
  - Transportation department approvals (esp. for haz-mats)
- Unique requirements
  - Environmental (e.g., temp, humidity, purges)
  - Vibration mitigation and monitoring
  - Time-sensitive components
  - Safety

I&T Lessons Learned

and Helpful Hints

Design Considerations for I&T

- Modularity of spacecraft bus subsystems
  - Facilitates ease of integration
  - Allows flexibility in integration sequence if subsystem delivery is delayed
- Flight interfaces (subsystem-payload, payload-instrument, vehicle-payload)
  - Standardized
  - Easily verifiable; incorporate parallel test connectors if necessary
  - "Quick-connect" fasteners (e.g., shuttle payload retention latches)
  - Avoid "blind mate" connectors
- Hardware locations to accommodate prelaunch "late" access to:
  - Higher-maintenance components for repair or replacement
  - Interfaces to accommodate late deliveries or manifesting
  - Connectors for battery charging, pyro arming, flight software updates, drag-on power
  - Servicing ports and red/green tag items (e.g., covers, safe plugs)
- GSE design factors to consider for integrated vehicle operations
  - Tetherable (e.g., IEH-3 covers)
  - Fixed or removable platforms (internal, external)
  - Power requirements
  - Safety
- New technologies
  - Inductive (wireless) power transfer for integrated internal elements and umbilicals
  - Robotics for hazardous ground operations
  - Automated testing and self-diagnostics

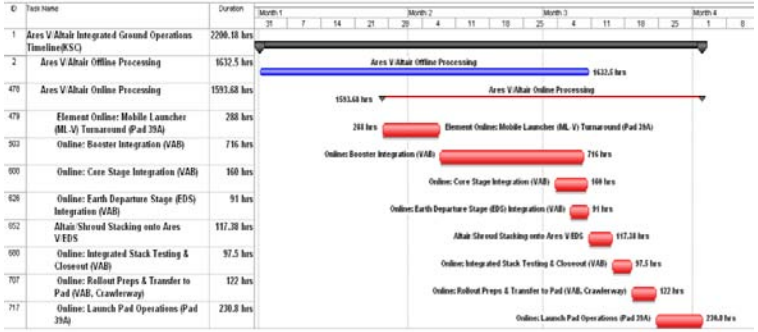
Preplanned Schedule & Estimated Resources

- Includes: personnel, equipment, facilities, procurements
- Initially developed by projects during proposal phase
  - Based on first-order estimates for individual tasks
  - Constrained by cost and schedule limits
  - I&T support required typically underestimated
  - "Easier to ask forgiveness than permission"
- I&T schedule reserve for projects (typ. for GSFC)
  - Two months of funded schedule reserve per year
  - Covers start of I&T to shipment to launch site (or to planned storage)
- Assumes that everything will run smoothly and fall into place

Month / Tasks / Resources	Thru Nov '06	Dec '06	Jan '07	Feb '07	Mar '07 [2]	Apr '07	May '07	Jun '07	Jul '07	Aug '07
	I&T Planning, Project Support	TC ID, I&T Preps, Scripts, TC Tng	I&T Preps, Scripts, TC Tng	I&T Preps, Scripts, TC Tng	303/BCE Setup, Laser/LEA, Heaters & T'stats	Optics & Detector, Scope, Fiber,MEB, Radiator, Fcn'l Test	Fcn'l Test, Alignment, CPT, Cal, Move to B.7, EMC	EMC, AVT, Staking, Vibe, AVT	CPT, Blankets, T'Bal, T'Vac	T'Vac, AVT, CPT, Mass, Cal, PSR
I&T Manager (1 N)	0.63/mo [3]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
I&T TC's (2 N)		2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Systems Engineer (1 N)					0.40	1.00	1.00	1.00	1.00	1.00
BCE Lead (1 N)				0.50	0.40	0.50	0.50	1.00	1.00	0.50
BCE Engineerr (1 C)					0.40	1.00	1.00	1.00	1.00	1.00
BCE Technician (1 C)					0.20	0.50	0.50	0.50	0.50	0.50
Laser Lead (1 N)					0.08	0.20	0.20	0.20	0.20	0.50
Optics Lead (1 N)					0	0.50	0.50	0.50	0.50	0.25
Optics Engineer (1 N)					0	0.50	0.50	0.50	0.50	0.25
Thermal Lead (1 N)					0	0.25	0.25	0.25	1.00	0.75
Thermal Engineer (3 N)									3.00	1.50
Electrical Lead (1 N)					0.20	1.00	1.00	1.00	1.00	0.50
Electrical Technician (1 C)					0.20	1.00	1.00	1.00	0.50	0.50
Mechanical Lead (1 N)					1.00	1.00	1.00	1.00	1.00	1.00
Mechanical Engineer (1 N)									1.00	
Mech.Design Engineer (1 C)						1.00	1.00	0.50	0.50	0.25
Mechanical Technician (1 N)					0.50	1.00	1.00	1.00	1.00	0.50
Software Lead (1 N)					0	0.25	0.25	0.25	0.25	0.25
Contamination Lead (1 N)					0	0.25	0.25	0.25	0.25	0.25
Instrument Scientist (1 N)					0.3	0.3	0.3	0.3	0.3	0.3
Data Analyst (1 C)				0.3	0.3	0.3	0.3	0.3	0.3	0.3
Total FTE's	1.04	3.00	3.00	3.80	6.98	13.55	13.55	13.55	17.80	13.10
Cleanroom: 33/F303(2),7/11(2+1)					$2K	$2K	$ 4K	$ 1K	$ 1K	$ 1K
EMC (30), Vibe (10), Mass (10)							$10K	$30K		$10K
Thermal-Balance/Vacuum (130)									$100K	$30K
Total Facilities Costs					$2K	$2K	$14K	$31K	$101K	$41K

What Actually Happens

- I&T is the phase of development that, after all others, is typically left with the least remaining reserve time to complete
- Additional time needed for I&T "Overhead"
  - Meetings (a.m., pretask, shift hand-over)
  - Procedure review and approvals
  - Task preparations and set-up
  - Crew startup, breaks, etc.
  - Hardware moves between facilities
  - Contamination control (e.g., tools)
  - QA and safety monitoring
- Unanticipated problems
  - Flight hardware and GSE failures
  - Interface incompatibilities
  - Facilities and weather disruptions
  - "Operator error"



- Delays
  - Late deliveries of hardware, subsystems
  - Design modifications
  - Facilities or personnel scheduling
  - Result in less overall time for I&T (since launch date usually fixed)

I&T Technical Tips

- Test and verification
  - Fit-checks and interface simulations for hardware prior to integration (ETU's, flatsats)
  - "Gap" testing may be required for some deliverables; covers any discrepancies between vendor flight certifications and project verification requirements
  - Verify all interfaces (copper path)
  - Fully test at each stage of integration, level of assembly
  - Don't short-change the test program; develop "incompressible test list"
- Test conductors
  - Ensure adequate staffing for planned test schedule
  - Team comprised of most (if not all) flight/mission operations team
  - Training: flight system familiarization, ground system ops, proc/display generation
- Safety and mission assurance
  - Balance oversight with common sense; more doesn't necessarily mean greater success, or safety (e.g., steel-toed shoes)
  - Don't ignore unexplained anomalies – they usually come back to haunt you
- Self-certifications for I&T engineers & managers
  - Crimping and harness fabrication and/or inspection
  - Mate/demate
  - Facility-specific training (incl. cleanroom cert)
  - ESD

General Hazards

All Require Special Certifications

- Lifts
  - Personnel and equipment certification
  - Generally prohibited during severe-weather
- Pyrotechnic (pyro)
  - RF silence during pyrotechnic connections
  - Unique test equipment (e.g., "Alinco" meters)
- Laser
  - Pre-operation eye exam typically required
  - Cleanroom access restrictions
- Heights
  - Personnel harnessing
  - Equipment tethering
- Pressures
  - Gases
  - Liquids
- Radiation
  - Ionizing: includes radioactive materials, x-rays
  - Non-ionizing: includes optical, infrared, microwaves

I&T Leadership

- Don't take for granted that delays will occur and will be acceptable
  - Keep everyone, including leads and vendors, appropriately accountable
- Be honest with team about when tasks need to be completed
  - Convey realistic schedule without undue "padding"
  - Develop daily schedules
- When a scheduled task is delayed, back-fill with something else
  - Keep things moving
  - Shoot for earlier-than-required completion
- Scheduling shift support
  - Develop long-range (e.g., monthly) support schedule
  - Respect personal restrictions (e.g.,. religious holidays, family needs)
  - Discuss w/ team preferred approach (e.g., rotating or fixed graveyard)
  - Support unpopular shifts with rest of team
- Do what makes wense
  - Challenge "status quo" when appropriate
- Learn from your mistakes
  - Accept objective criticism and suggestions
  - Admit when you're wrong
  - Remember: It's not about you

I&T Communications

- Be specific regarding requests for support, action
  - Who, what, when, where
- Be open to meaningful technical debate
  - May need to get all stakeholders in one room to discuss
  - Need to balance debate with timely decision and action
  - Determine if obstacles are real or perceived
  - Case in point: LRO composite abrading issue
- Conduct team meetings effectively
  - Start on time, end on time
  - Try to limit weeklies to 1 hour, dailies to 30 minutes, pretask to 15 minutes
  - Limit to topic at hand, with post-meeting discussion if necessary
  - Refreshments (e.g., donuts, pastries) tend to encourage attendance

- Listen to "gut-level" engineers who have a wealth of experience
  - Trust good engineering judgement from good engineers
  - Their input may be more valuable than specs, standards, and documentation
- Interact well with the I&T team
  - Be "on the floor" (make rounds) as much as possible, yet avoid "hovering"
  - Keep personal issues and negative temperament in check (e.g., ODERACS)
  - Socialize when appropriate
  - Keep things light, esp. when team is stressed . . .

Unique Aspects of I&T

for Human Spaceflight Missions_

- Safety
  - Flight systems
  - Vehicle requirements
  - Ground and GSE
- Some additional testing
  - Redundant systems
- Crew training
  - Mission simulations
  - Flight system familiarization
- Sharp-edge inspections
  - Typically performed at launch site
- Human involvement means human risks
  - Close working/personal relationships

Flight Systems Integration & Test

STS-107 Accident Investigation

- Immediate actions taken
  - Impoundment of GSE and documentation at GSFC
  - GSE at KSC impounded; release required formal request/approval
- Initial "soul-searching"
  - Could the work we did have been a contributing factor? Did we miss something?
- FREESTAR Debris Identification and Reconstruction Team (DIRT)
  - Comprised of a few individuals intimately familiar with the payload hardware
  - Called on to be at KSC to identify hardware as it came in from Texas
  - Identified payload hardware, forwarded instrument photos to experimenters
  - Lasted several months (on/off), with over 230 items positively identified
- I&T team is uniquely qualified to support hardware identification efforts
  - Be prepared to support such an investigation
  - Establish plans and protocols in advance of a potential accident
  - Support possible post-accident legal investigation (e.g., SHab)

I&T Mishaps and Failures

Some Big, Some Small

Flight Systems Integration & Test

Apollo 1 (AS-204)

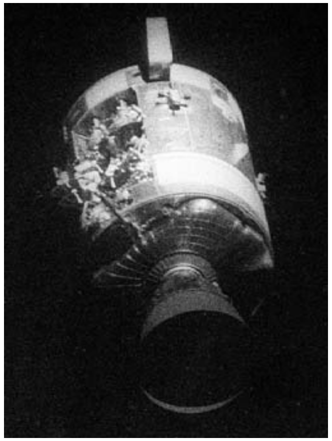
January 1967

- Hardware: Command Module (CM) 012
  - Pure oxygen environment
  - Inside-opening door
  - Combustible materials in cabin
- Operational conditions: Apollo 204 plugs-out integrated test
  - Cabin pressurized above atmospheric to simulate mission differential
  - Lack of emergency response personnel and equipment at pad
- Incident: fire in the crew cabin
  - Approx. 10.5 hours into test, and 5.5 hours after flight crew ingress
  - Fire spread to upper areas of pad, with some difficulty in egress for ground personnel
  - Rupture of spacecraft, loss of flight crew, injury to ground crew, damage to facilities
- Cause: not conclusively determined
  - Suspected short in cabin internal wiring
  - Resultant spark within pressurized oxygen environment resulted in fire
- Lessons learned for I&T:
  - Avoid considering ground testing as "routine" or safe, particularly for hazardous operations
  - Adequately prepare for emergency egress and response
  - Design systems (incl. ground) to properly control hazards (e.g., dual-fault tolerance)

Apollo 13

April 1970

- Hardware: Service Module (SM) O2 Tank #2
  - Dropped during Apollo 10 integration w/ probable (unsuspected) damage to internal fill line
  - Tanks originally designed for 28 VDC SM power; redesigned to run off 65 VDC ground power
  - Heater thermostat switches overlooked in modification
- Operational conditions: Apollo 13 preflight testing and mission operations
  - Tank would not empty correctly; heaters used to boil-off excess for 8 hours (@ 65V)
  - Thermostat switches probably welded shut, allowing temp. in tank to exceed 1000° F (538 C)
  - Damage to teflon insulation protecting wires to tank's internal power fan
- Incident: SM O2 tank in-space explosion
  - 56 hours into mission, after crew activated power fans for "cryo stir"
  - Damage to SM enroute to moon; loss of O_2, power, water, propulsion
  - Loss of mission (LOM), potential loss of crew (LOC)



- Cause: previously damaged/exposed fan wires shorted
  - Spark within pure O_2 environment resulted in Tank #2 explosion
  - Tank #2 explosion caused collateral damage to Tank #1
- Lessons learned for I&T:
  - Fully inspect (or discard) safety-critical hardware damaged during I&T
  - For design mods, conduct comprehensive review, and independent review for critical systems

Spacelab 2

September 1984

- Hardware: Spacelab and GSE
  - Integrated Spacelab Subsystems
  - Ground power system and command/data system
- Operational conditions: Level II/III mission sequence test
  - Nominal mission simulation of integrated Spacelab subsystems
  - 8+ hour test, requiring large team of engineers and technicians
- Incident: sudden deactivation and reactivation of Spacelab
  - Less than a half-hour prior to scheduled deactivation
  - Power to entire Spacelab flight system lost, with subsequent system errors
  - Power immediately restored, with potential damage to flight systems
  - Required several additional hours of reconfiguration by test team
- Cause: inadvertent emergency power-down by technician on floor
  - While awaiting his next step in the procedure, pressed the "lamp test" button
  - Button was actually the emergency power down switch
  - Tech was experienced enough: switched power to "local" control, then immediately reactivated system (presumably hoping no one would notice)
- Lessons learned for I&T:
  - Avoid distractions during a test (esp. if tempted by boredom)
  - Avoid immediately reactivating systems following an unplanned shutdown
  - First, secure and determine configuration of system, then perform an orderly reactivation

Hubble Space Telescope (HST)

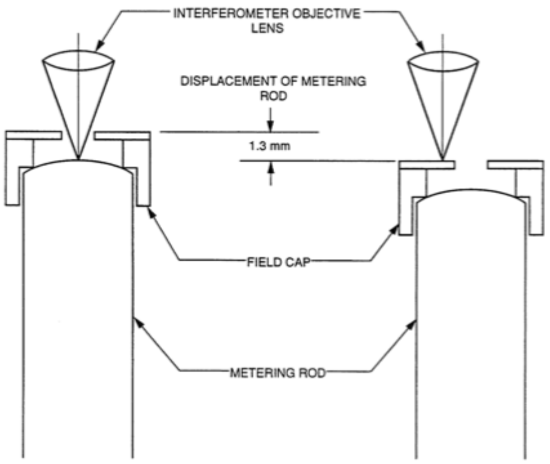
June 1990

- Hardware: HST primary mirror and reflective null corrector (RNC)
  - Primary mirror: 2.4m-diameter aspheric concave hyperboloid
  - RNC – null compensator (GSE) used to measure the shape of the mirror
- Operational conditions: mirror null test measurement using RNC
  - Interferometric measurement using transmission sphere and null compensator
  - RNC was modified from one used on a smaller mirror prototype
  - Metering rods centered with respect to interferometric beam
  - Field caps installed on rods to ensure alignment
- Incident: shape of flight mirror incorrectly measured during testing
  - Spherical aberration observed in on-orbit images from multiple instruments
  - Significant loss of science data
- Cause: RNC assembled incorrectly
  - Spacing of RNC elements during mirror testing was incorrect
  - No dimensional verification performed on RNC following assembly
  - Single test method depended upon for important measurement
  - Overreliance on quality assurance personnel to ensure proper procedures were followed
  - Errors discovered using other GSE reportedly discounted by contractor, with insufficient analysis
  - Budget and schedule constraints were factors in failure to conduct independent or end-to-end test

Flight Systems Integration & Test

Hubble Space Telescope (HST)

June 1990

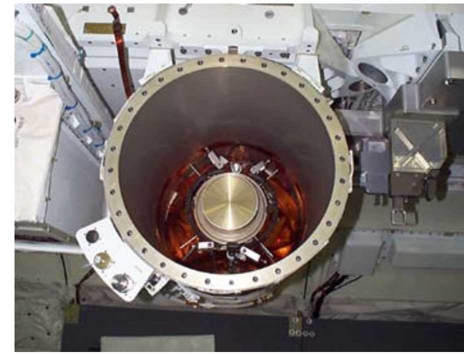


Before Repair After Repair

- Lessons learned for I&T:
  - Perform independent verification & validation (V&V) of critical test configurations and equipment
  - Perform end-to-end testing of final flight configuration
  - Heed reported test errors, however in-credible
  - Conduct risk assessments and trades if independent V&V or end-to-end testing is not performed
  - Establish clear roles and responsibilities of organizations and individual team members
  - Maintain rigorous documentation
  - Practice open and inclusive communication

MightySat (STS-88)

October 1998



- Hardware: MightySat and canister
  - Hitchhiker side-mounted payload with opening lid
- Operational conditions: orbiter integration
  - Horizontal integration at Orbiter Processing Facility (OPF)
  - MightySat payload servicing and close-outs with lid open
- Incident: small screw found missing
  - Suspected that screw was accidentally dropped into canister
  - Inspection inconclusive; attempted retrieval unsuccessful; risk to ejection on-orbit
  - Required canister deintegration, satellite removal, and reintegration (all within 24 hours)
- Cause: insufficient integration team discipline in handling fasteners
  - Although screw was never found, lack of good handling practices was contributor
- Lessons learned for I&T:
  - Handle hardware, particularly non-tethered items, with care
  - Cover open cavities of flight hardware whenever possible
  - Incorporate captive fasteners and tools

WIRE Satellite

March 1999_

- Hardware: Wide-field InfraRed Explorer (WIRE) Small Explorer Satellite
  - Astronomical telescope; solid hydrogen cryostat with pyrotechnic-ejectable cover
- Operational conditions: postlaunch mission operations
- Incident: cryostat cover ejected prematurely
  - Electronics startup transient to pyrotechnic ejection circuit
  - Rapid boil-off of Hydrogen resulted in loss of satellite stability and attitude control
  - Loss of original science mission, impact to follow-on infrared astronomy mission
- Cause: digital logic error in pyro control box
  - Variable activation characteristics of FPGA not adequately considered in design
  - Source of transient observed during spacecraft I&T not correctly identified

WIRE Satellite

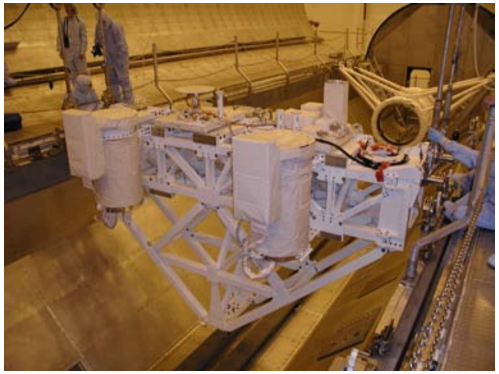
March 1999_

- Root cause: inadequate interorganizational communication
  - Compromise of insight/oversight of instrument electronics design
  - Inadequate instrument electronics peer review
  - Lack of clarity regarding "who was in charge of what"
- Root cause: lack of complete end-to-end testing of pyro circuit
  - Poor fidelity of pyro test box design
  - Inadequate troubleshooting of anomalous signal observed during testing
- Lessons learned for I&T:
  - Functional testing should be supplemented with robust testing for anomalous behavior
  - Fully investigate and understand causes of anomalies experienced during I&T
  - Perform full end-to-end testing in flight configuration, particularly for critical systems
  - Ensure roles and responsibilities are clear
  - Ensure open technical communication, conduct robust peer reviews

FREESTAR RS-422 Interface

May 2002

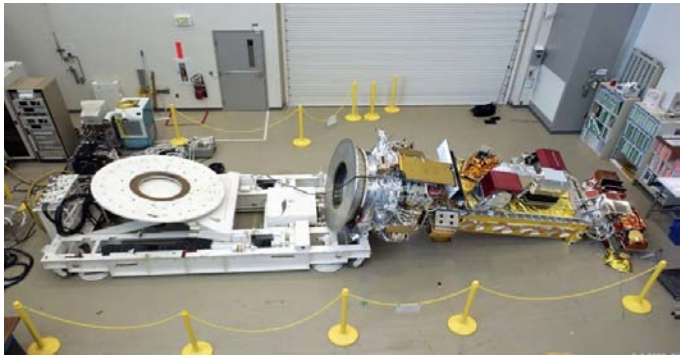
- Hardware: FREESTAR payload (STS-107)
  - Payload RS-422 orbiter interface for Payload and General Support Computer (PGSC)
- Operational conditions: payload in transport canister with SpaceHab
  - Horizontal integration at Orbiter Processing Facility (OPF)
  - Afternoon prior to orbiter installation and subsequent interface verification test (IVT)
- Incident: RS-422 telemetry interface polarity found to be reversed in documentation
  - Discovered following I&T and consult with JSC electrical lead engineer
  - Not caught earlier during testing since GSE interface was also reversed (2 wrongs made right)
  - Too late to modify orbiter interface; decided to perform internal pin-swap
  - Required access to payload in transport canister, just prior to lift to orbiter
  - I&T manager/engineer able to effect modification without technician present (CCH-certified)
- Cause: lack of proper verification of hardware against orbiter ICD
  - Some ambiguity in orbiter interface control document (ICD) and payload schematics
  - GSE wiring reversal masked pin reversal at flight interface
- Lessons learned for I&T:
  - Ensure schematics and interfaces are clear and fully understood
  - Validate GSE interface to flight system; verify no double-errors
  - Beneficial for I&T manager and engineers to be hardware-certified



NOAA N-Prime Satellite

September 2003

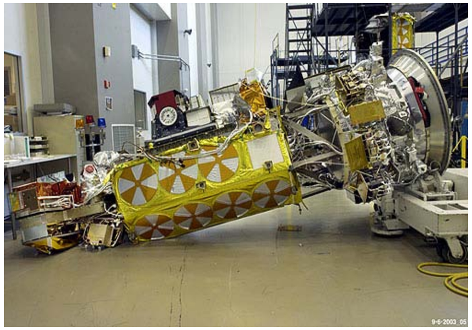
- Hardware: NOAA N-Prime satellite and turn-over cart (TOC)
  - Rotation of satellite to horizontal position requires securing it to the TOC using 24 bolts
  - 3130 lbs (1420 kg), 13.75 ft (4.2 m) long, 6.2 ft (1.9 m) diameter
- Operational conditions: integration of instrument on spacecraft
  - Task rescheduled to 3 days earlier than originally planned (to a Saturday morning)
  - Satellite's batteries fully charged, prop system pressurized, separation band tensioned
  - Access to instrument necessitated rotation of satellite
  - TOC plate bolts had been removed for use on another project (not communicated to team)
- Incident: satellite fell off of TOC during rotation
  - Spacecraft slipped, falling approx. 3 feet (1 m) to floor and tipped over in process
  - Severe damage to satellite
- Cause: TOC bolts not installed on adapter plate
  - Loss of satellite restraint during rotation
  - Multiple root causes related to I&T operations (as well as systemic/organizational issues)



Note: Location of mishap at contractor facility in Sunnyvale, California

NOAA N-Prime Satellite

- Root cause: TOC plate not secure because team failed to execute procedures
  - TOC configuration was verified only via paperwork, not visually
  - Team was narrowly focused and did not notice state of hardware
  - Comment by tech supervisor regarding missing bolts was dismissed
  - Lead tech & inspector signed-off TOC verification without witnessing
  - Violations were reportedly commonplace



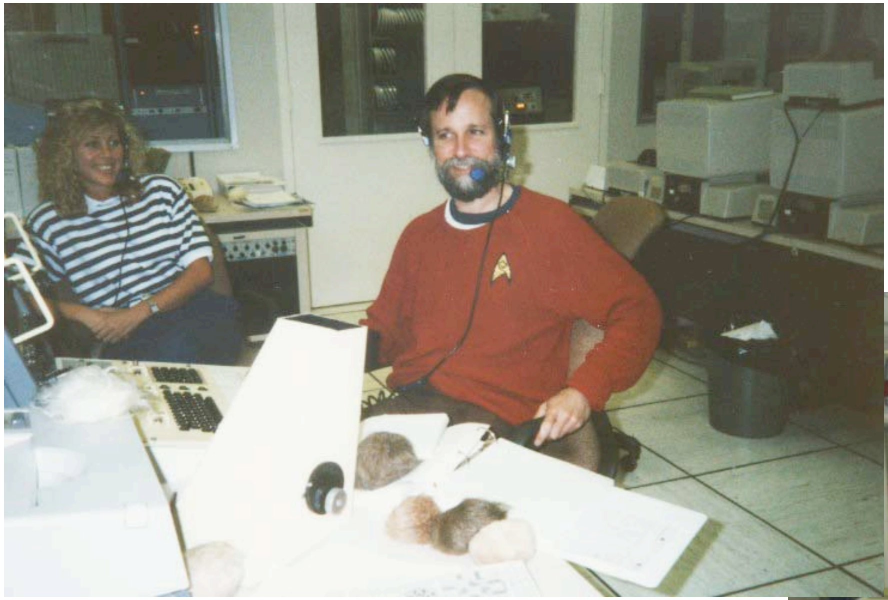
- Root cause: lack of operational discipline among I&T team
  - Complacency impaired the team; operation was routine and low-risk
  - Crew fatigue and time-constrained schedule (weekend day)
  - Incomplete coordination regarding GSE use and status
  - Late notification of operation schedules
  - Procedures contained ambiguous terminology and redlines
- Root cause: unsafe supervision practices
  - I&T manager and test engineer failed to provide adequate supervision and violated procedures
  - Waived safety presence, notified inspectors late, poor documentation, misuse of redlines
  - Hurried task planning resulted in hastily formed team; less than effective comm and responsibility
- Lessons learned for I&T:
  - Develop clearly written procedures - then follow them; avoid redlines
  - However, don't depend on documentation to verify configuration of hardware; conduct walk-down
  - Practice effective communication, particularly during hazardous operations
  - Plan well and avoid last-minute scheduling with inadequately prepared team

The Lighter Side of I&T

Flight Systems Integration & Test

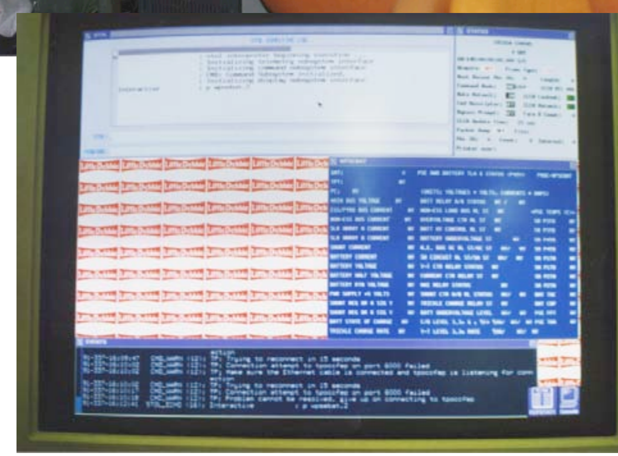
"Star Trek Day"

Spacelab ASTRO-I Experiment Testing

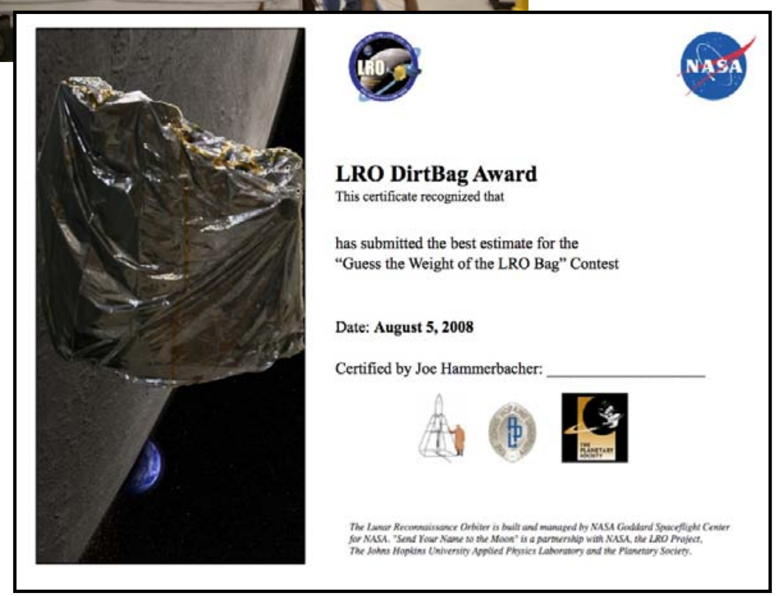


Flight Systems Integration & Test

SAMPEX TC's for "Little Debbie"



LRO "Guess the Weight of the Bag" Contest



LRO DirtBag Award

This certificate recognized that

has submitted the best estimate for the
"Guess the Weight of the LRO Bag" Contest

Date: **August 5, 2008**

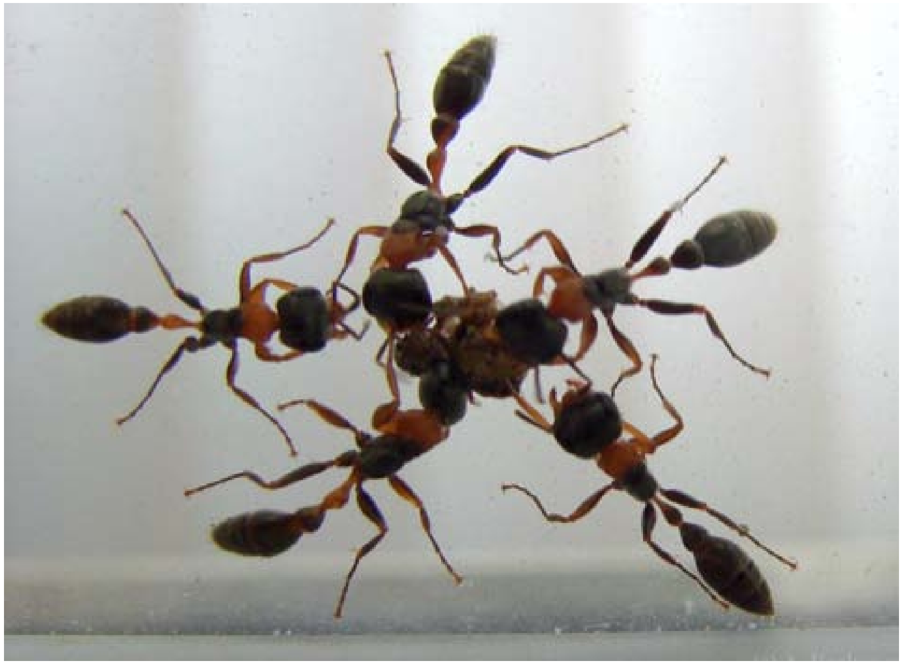
Certified by Joe Hammerbacher: ____________________

The Lunar Reconnaissance Orbiter is built and managed by NASA Goddard Spaceflight Center for NASA. "Send Your Name to the Moon" is a partnership with NASA, the LRO Project, The Johns Hopkins University Applied Physics Laboratory and the Planetary Society.

Any questions, please email:

michael.r.wright@nasa.gov

Small-Team Activity



I&T Scenario – Your Task

- Develop I&T flow/sequences for fictitious mission
  - Include bus, observatory, launch site operations
- Identify any special I&T requirements, tasks, equipment
- Identify any potential hazards
- Small-team logistics:
  - Relocate to rocket lab
  - Groups of 4 to 6
  - Present final version to class

I&T Scenario – System Description

- Asteroid mission (in-house)
  - 3 instruments and small probe
  - Some redundancy in power and C&DH systems
  - Launch on a Delta-II from KSC
- Subsystems include:
  - Monopropellant attitude control system (tank, thrusters)
  - GNC sensors (star tracker, IMU)
  - Power system (w/ batteries, deployable solar arrays)
  - C&DH
  - Communications (w/ gimbaling HGA)
  - Probe separation system (pyro-actuated)
- Instruments:
  - Imagers (low-, high-res)
  - Spectrograph
  - Soft-landing probe (w/ battery, camera, spectrometer, tlm xmitter)
- ETU's exist for:
  - Spacecraft structure
  - C&DH
  - Comm transceiver
  - Power avionics
  - Probe

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