



GN&C Lessons Learned and Associated Best Practices

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Presentation Outline

- **Acknowledgement**
- **NESC Background**
 - NASA Technical Fellows
- **Why Do We Care About Lessons Learned ?**
- **Characteristics of a Learning Organization**
- **Some Disturbing Recent GN&C Trends**
- **Common GN&C Pitfalls**
- **NESC's 22 GN&C Best Practices**
- **Discussion of GN&C Best Practices vs. Real-World Mishaps**
 - Lewis spacecraft, X-43A hypersonic vehicle, Landsat-6 spacecraft, Conestoga launch vehicle, Ariane 5 Flight 501,
- **NESC Academy**
- **7 Fundamental Elements of Flight Rationale**
- **Concluding Remarks**
- **References**



Acknowledgement



The GN&C lessons learned and the associated best practices highlighted in this presentation were derived from multiple NASA's mission experiences. The author would like to acknowledge all the dedicated GN&C engineers who worked on those spaceflight projects who invested their time and energy to document their lessons learned for future generations of GN&C engineers..



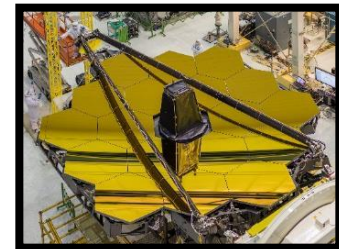
NASA Engineering & Safety Center (NESC) Background



The NESc: Bottom Line – Up Front



- ✓ Independent technical assessment is a critical component of the safety and mission success of NASA's programs
- ✓ NESc provides technical support to and independent technical assessments for all of the Agency's programs
- ✓ NESc has established itself as the “value added” independent test and analysis organization for the Agency with over 700 Assessments in 13+ years
- ✓ NESc was a key contributor to the Space Shuttle Program return to flight and the safe and successful fly-out of the program
- ✓ With two human space flight programs in development (Commercial Crew Program, CCP, and Exploration Systems Development, ESD), one in operation (International Space Station, ISS), and multiple earth and planetary science programs in every lifecycle phase, ***a robust independent technical capability*** is necessary for NASA to continue to accomplish its mission
- ✓ NESc workload remains high and is distributed across all of NASA's Centers and Mission Directorates





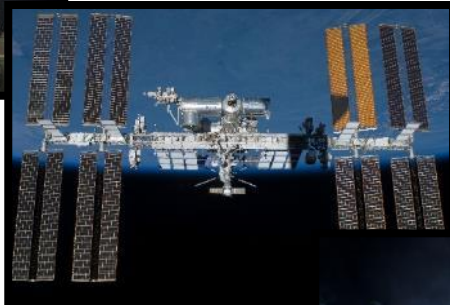
NESC Background and Mission



Space Shuttle



International Space Station



Exploration



- ✓ NESC was established in July 2003 in response to the Columbia accident
- ✓ NESC highlights NASA's traditional safety philosophy:
 - *Strong in-line checks and balances*
 - *Healthy tension between organizational elements*
 - *Value-added independent assessment*
- ✓ NESC provides independent assessment of technical issues for NASA programs and projects

NESC is cultivating a Safety culture focused on **engineering and technical excellence**, while fostering an **open environment** and attacking challenges with **unequalled tenacity**



NESC Model



- ✓ Institutionalized “Tiger Team” approach to solving problems
- ✓ Agency-recognized NASA Technical Fellows lead Technical Discipline Teams (TDT)
 - *“Ready” experts from across NASA, industry, academia and other agencies*
 - *Diverse, expert technical teams provide robust technical solutions*
- ✓ Assemble independent, diverse, expert technical teams that provide robust technical solutions to the Agency’s highest-risk/most complex issues
 - *NESC involvement ranges from supporting reviews, augmenting project teams, and solving problems through independent test and analysis, to exploring alternate design concepts*
- ✓ Strong Systems Engineering and Integration function for proactive trending and identification of problem areas before failures occur



Artist Concept of Orion, Space Launch System (SLS), and Mobile Launcher Platform (MLP) Rolling Out of VAB

Focus on technical rigor and engineering excellence



NASA Technical Fellows



- ✓ Senior-level engineers and scientists with distinguished and sustained records of technical achievement
- ✓ Agency's leading experts in their respective technical disciplines
- ✓ Lead and maintain their individual NESC Technical Discipline Teams with ready-experts
- ✓ Provide leadership and act as role models for NASA discipline engineering communities beyond the Technical Discipline Teams
- ✓ Provide technical consistency across NASA through inputs to Agency-level specifications/standards and tailoring of those standards for Programs and projects
- ✓ Promote discipline stewardship through workshops, conferences and assorted discipline-advancing activities
- ✓ **Ensure lessons learned are identified, widely shared across engineering organizations, and incorporated into Agency processes**
- ✓ Serve as NASA Capability Leaders, assessing technical discipline readiness to execute current and future missions; conduct discipline specific gap analyses to identify areas that require strategic investment to develop fundamental engineering sciences; and provide recommendations to promote capability health



NASA Technical Fellows



Michael Aguilar
Software
LaRC



Thomas Brown
Propulsion
MSFC



Neil Dennehy*
GN&C
GSFC



Michael Dube
Mechanical Systems
GSFC



Oscar Gonzalez
Avionics
GSFC



Jon Holladay
Systems Engineering
GSFC



Chris Iannello
Electrical Power
KSC



Curtis Larsen
Loads & Dynamics
JSC



Joseph Minow
Space Environments
MSFC



Daniel Murri
Flight Mechanics
LaRC



Cynthia Null
Human Factors
ARC



William Prosser
NDE
LaRC



Ivatury Raju
Structures
LaRC



Steven Rickman
Passive Thermal
JSC



Henry Rotter
Environmental Control/
Life Support
JSC



Richard Russell
Materials
KSC



David Schuster
Aerosciences
LaRC



Upendra Singh
Sensors/
Instrumentation
LaRC

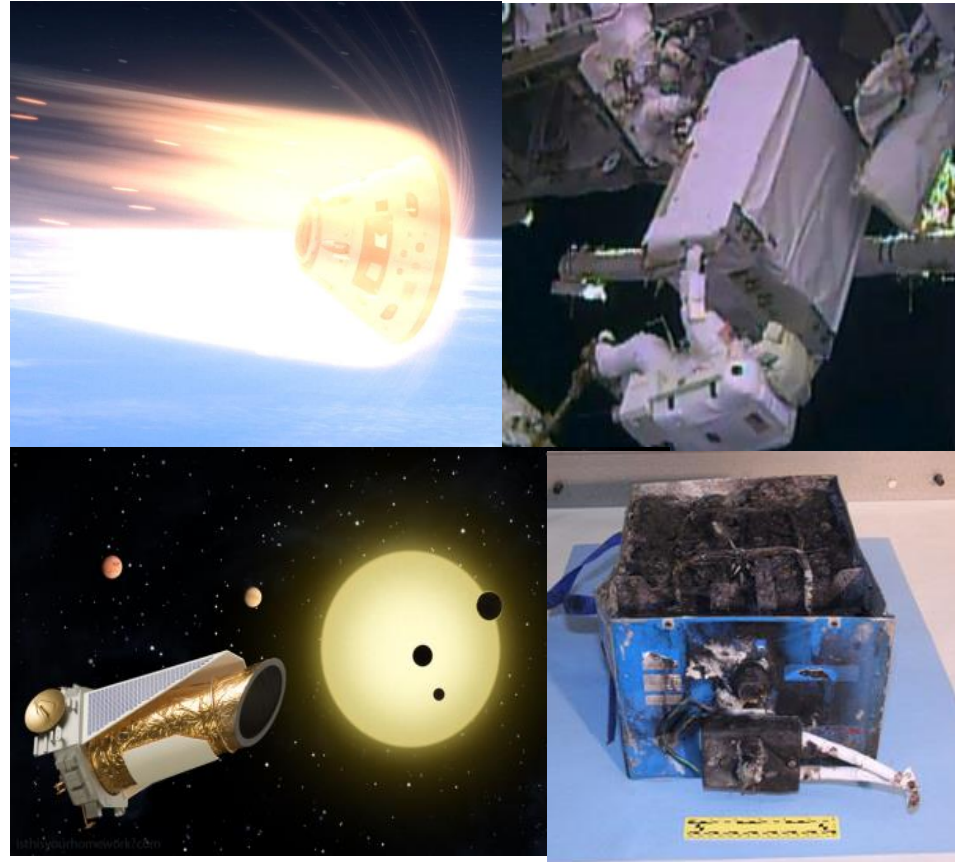
* = Technical Fellow Office Lead
GN&C Lessons Learned Invited Presentation at ESA/ESTEC



Examples of Current and Recent NESC Technical Assessments



- **CCP Avionics/GN&C Architecture**
- **Kepler Spacecraft 2-Reaction Wheel Attitude Control**
- ISS coolant loop anomaly resolution
- Independent Modeling and Simulation for CCP EDL
- **Alternative Reaction Wheel Source**
- SLS Booster Interface Loads
- JWST Bearing Lubricant Study
- Independent Modeling and Simulation of Exploration Systems
- JWST Sunshade Venting Analysis
- Mars Insight Lander ground wind loads
- Orion TPS Margin Study
- Dreamliner Battery Incident Support

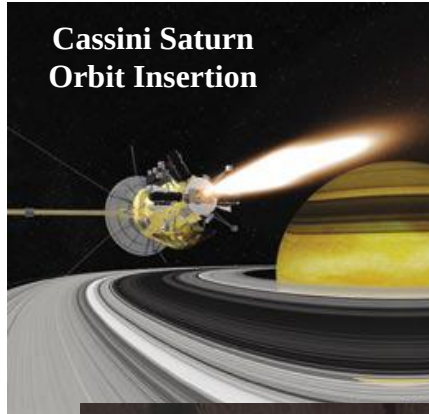




Past Experiences of the NESC GN&C Team

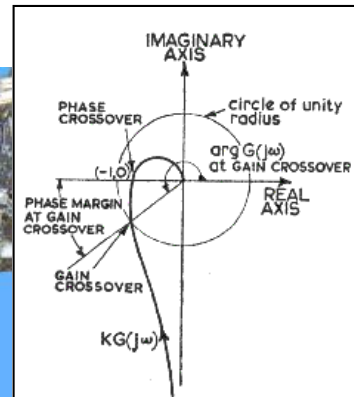


GN&C Recommended Best Practices

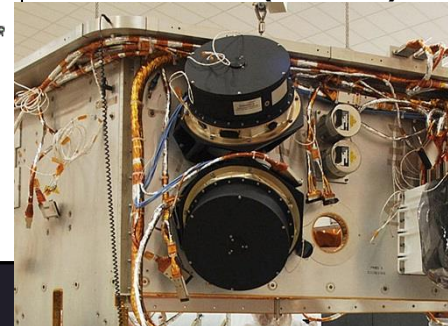


Cassini Saturn
Orbit Insertion

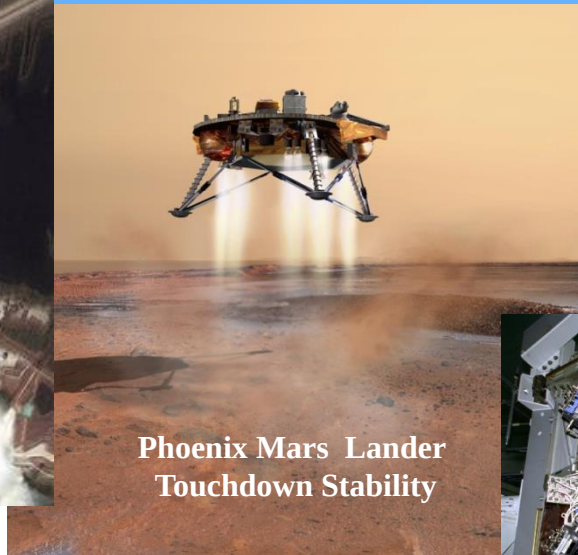
Orbiter Repair Maneuver



Spacecraft Reaction
Wheel Anomalies
and Failures (Various)



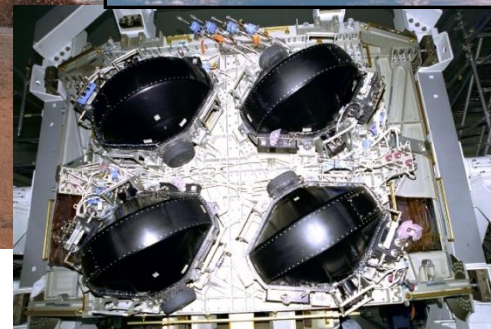
Orion SM Propellant
Slosh Impact on Stability
of Ares-1 FCS



Phoenix Mars Lander
Touchdown Stability



Hubble Space
Telescope
System Health and
Attitude Observer
Anomaly (Gyros)



ISS Control Moment
Gyroscope Failure



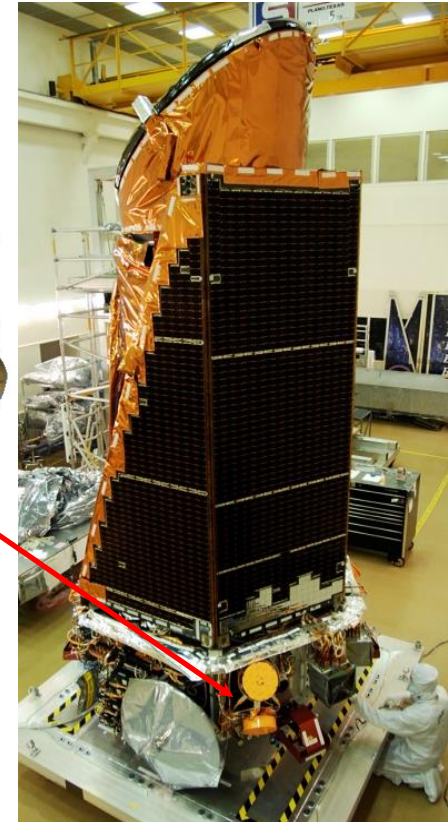
A Specific GN&C Assessment Example: Kepler 2-Reaction Wheel Attitude Control



- Kepler completed its 3.5-year prime mission in November 2012.
- RW-2 failed at the 3.3-year mark (in July 2012).
- Kepler suffered its second wheel failure shortly after the workshop (May 2013) prompting development of 2-Wheel attitude controller at Ball (prime contractor)
- NESC GN&C TDT coordinated the Kepler Pointing TIM held in September 2013 at NASA ARC to review all RFI responses and to discuss attitude control capabilities to accomplish new types of Kepler science.
- NESC subsequently sponsored research at Naval Postgraduate School (NPS) to investigate alternative methods for 2-wheel attitude control and propellant optimized attitude slewing.



Kepler Observatory
in I&T





Why Do We Care About Lessons Learned ?



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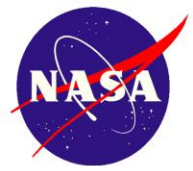
The Value of Capturing and Sharing Lessons Learned (1 of 2)



- Within the broad aerospace community, the importance of identifying, documenting and widely sharing lessons learned is broadly acknowledged.
- Documenting and sharing lessons learned helps managers and engineers to minimize project risk and improve performance of their systems.
- It is especially valuable when lessons learned can be leveraged on new system development projects to help overcome the team's unfamiliarity with previously identified technical pitfalls and challenges.
- However, significant lessons learned on a project often fail to be captured even though they are well known 'tribal knowledge' amongst the project team members.



The Value of Capturing and Sharing Lessons Learned (2 of 2)



- **A common occurrence on many projects is that the documentation of lessons learned for the benefit of the next generation of NASA engineers fails to happen for various reasons.**

- **Documenting lessons learned shouldn't wait until after launch or project closeout**
 - Documentation should take place immediately after the team has identified a lesson learned, while teams are still assembled and while memories are still fresh

- **Past studies have concluded that NASA needed better mechanisms for broadly sharing and infusing lessons learned across the Agency**
 - Lessons are documented but not truly learned (and must be re-learned!)
 - When surveyed, engineers responded that while they were knowledgeable about lessons generated by their own projects and centers, they knew much less about lessons generated elsewhere



Characteristics of a Learning Organization



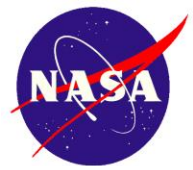
Characteristics of a Learning Organization



- According to the Columbia Accident Investigation Board (CAIB) report NASA: ***“has not demonstrated the characteristics of a learning organization.”***
 - Investigators observed that mistakes from the past were repeated
 - Lessons already learned and documented had to be re-learned
- **CAIB and Diaz Report Suggestions**
 - Critical to improve training through hands-on training and mentoring
 - Have all managers take yearly lessons learned review
 - Develop a system for people to share knowledge and lessons in one place
- **A ‘Learning Organization’:**
 - Changes its behavior based on experience
 - Promotes self-initiative, peer leadership and learning at all levels
 - Focus on individual responsibility for sharing and learning



A Learning Organization (1 of 2)



- **To be a true ‘Learning Organization’ NASA has recognized the need to do a better job of identifying, documenting and widely sharing lessons learned between centers from each of our development, flight or research projects**
 - With our NASA field centers spread around the country, there are very few built-in opportunities for cross-pollination among the technical workforce

- **Within NASA, the responsibility for overseeing and managing lessons learned belongs with the NASA Chief Engineer.**
 - One of the NASA Chief Engineer’s primary tools to execute this responsibility is the NASA Engineering Network (NEN), which houses the Lessons Learned Information System (LLIS).



A Learning Organization (2 of 2)



- Failing to be a Learning Organization leads to the undesirable behaviors where mistakes from the past are repeated and lessons already learned and documented have to be (painfully) re-learned
- Often it is the case that our widely dispersed engineering organizations there are very few built-in opportunities for cross-pollination among the technical workforce.
- Capturing lessons learned shouldn't wait until after launch or project closeout. The documentation of lessons learned should take place immediately after the team has finished its major effort, while teams are still assembled and while their memories are still fresh.

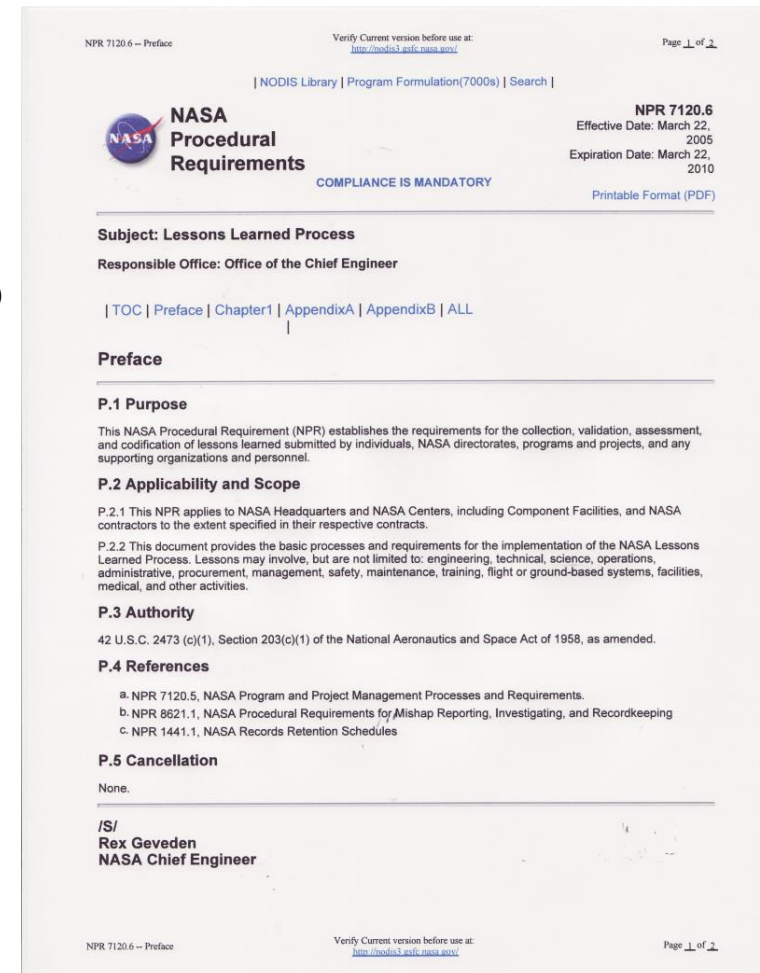
“A formal lessons learned process is a hallmark of a mature engineering organization, and it can provide an effective countermeasure to avoidable risk.”



Lessons Learned Practices at NASA Today

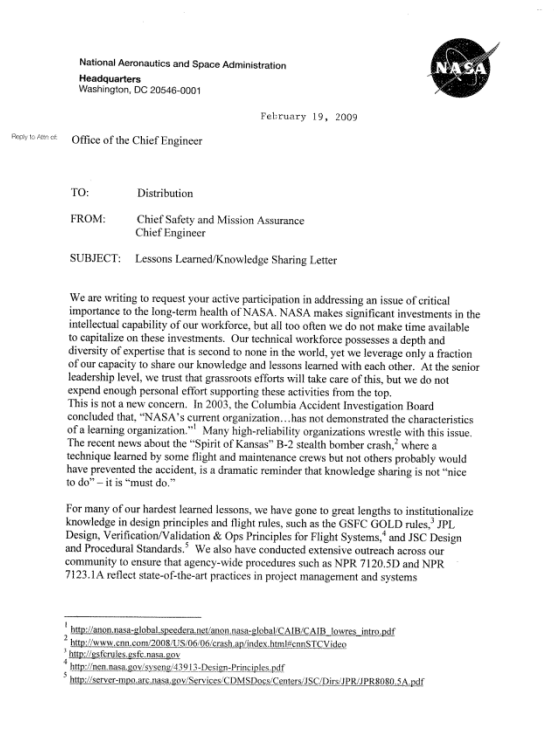


- **Covered by formal NASA Procedural Requirement (NPR 7120.6)**
 - Responsibility of the NASA Chief Engineer
 - Each Center appoints a Lessons Learned Center Data Manager and Oversight Committee
- **Principle: lessons learned will be infused into projects at key decision points**
 - Program/Project Manager leads the infusion
- **Tools**
 - NASA Engineering Network to facilitate engineering community collaboration and lessons identification
 - **NASA Technical Fellows identify and share discipline-unique lessons within their Community of Practice**
 - NASA Lessons Learned Database managed by Lessons Learned Steering Committee (NASA-wide membership)
 - Lessons Learned and Knowledge Sharing workshops
 - Academy of Program/Project and Engineering Leadership (APPEL) for professional development of NASA staff
 - ASK Magazine to communicate achievements and real life experiences





Lessons Learned/Knowledge Sharing Letter (Mike Ryschkewitsch/Bryan O'Connor, 19 Feb 2009)



engineering.⁶ We need to be vigilant in continuing to improve and grow these efforts to institutionalize our lessons and share these capabilities across the agency.

Our efforts to record knowledge and lessons at an institutional level in our processes and procedures are necessary but not sufficient. Within the context of NASA, learning has to take place on three levels. It has to reach our *individual practitioners*, through job assignments, formal training, knowledge sharing workshops, and membership in communities of practice. It also has to take place among our *teams*, through either sharing workshops or one-on-one mentoring and coaching. Finally, learning has to occur at the *organization* level. With our field centers spread around the country, there are very few built-in opportunities for cross-pollination among the technical workforce, so we have to employ through cross-agency knowledge sharing initiatives such as case study workshops, forums, publications, and communities of practice to build a broader learning organization.

NASA continues to implement new and innovative ways for our workforce to share their knowledge as part of their normal everyday work. It is critical that we support the capability to document and store our rich history in the form of lessons and knowledge in searchable and discoverable formats. We must ensure that we use technology so that it is a complement to (and not a substitute for) our face-to-face activities. The NASA Engineering Network⁷ offers easy methods to search for lessons and knowledge across the agency, and serves as a central portal for communities of practice in specific technical disciplines. With the addition of an open format lesson submission to NASA's Lessons Learned Information System (LLIS),⁸ our workforce can easily save daily work products containing valuable lessons and related contextual information with a few simple key strokes.

Examples of other key agency-wide resources include:

- Process Based Mission Assurance Knowledge Management System video nuggets and case studies⁹
- NASA Safety Center's Cases of Interest¹⁰
- Courses, forums (captured in a video library), case studies, and publications such as ASK Magazine and ASK the Academy offered by APPEL¹¹

Use of agency-wide resources help to advance and increase knowledge sharing across our workforce.

There are specific steps you can take to improve NASA's performance as a learning organization. At the conclusion of every significant development under your

leadership—when projects, instruments, subsystems, elements completes its work—the team involved should convene a sharing workshop to reflect on and capture its lessons learned. This shouldn't wait until after launch or closeout; it should take place immediately after the team has finished its major effort, while teams are still assembled and while memories are still fresh.

As a leader, you can play a critical role by modeling behaviors conducive to learning at the highest level of your organization. By holding your own internal sharing workshops and attending open-door knowledge sharing forums, you can send a powerful signal about the importance of making time for these activities. Your example can also encourage participation in activities that foster individual reflection about lessons learned, such as writing articles for practitioner-focused publications.

We must not forget the risk that we accept if we do not take the time to encourage our workforce to engage in sharing NASA's lessons and knowledge. We cannot afford to lose sight of the importance of continuing to improve our performance as a learning organization. Thank you for taking the time to help us institutionalize the sharing of knowledge and lessons learned from the top down. Your leadership in this area will make a real difference.

Bryan O'Connor
Bryan O'Connor

Mike Ryschkewitsch
Dr. Michael G. Ryschkewitsch

Chief Engineers Office
HQ/KAO/Mr. Hoffman
HQ/KGO/Ms. Smalley

Center Directors
ARC/200-1/Dr. Worden
DRFC/2004/Mr. Peterson
GRCC/3-2/Dr. Whitlow
GSFC/100.0/Mr. Strain
JPL/180-904/Dr. Elachi
JSC/AA/Mr. Coats
KSC/AA/Mr. Cabana
LaRC/102/Ms. Roe
MSFC/DA01/Mr. King
SSC/AA00/Mr. Goldman

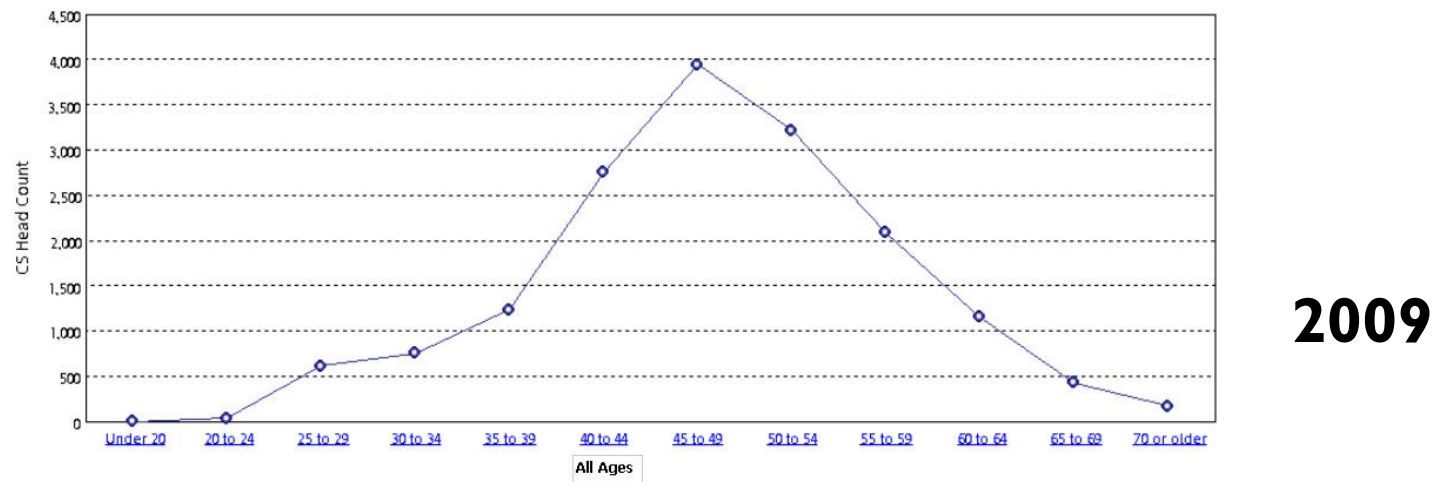
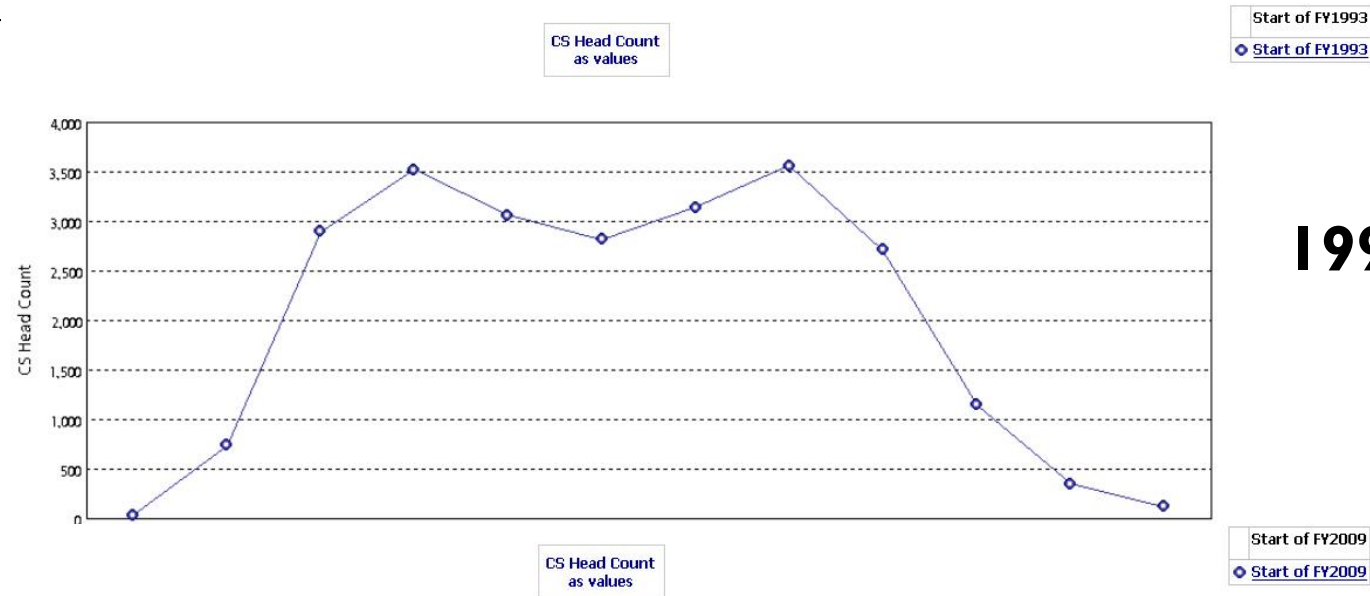
Engineering Directorates/EMB Members
HQ/KAO/Mr. Bullman
HQ/KAO/Mr. Ledbetter

“With our field centers spread around the country, there are very few built-in opportunities for cross-pollination among the technical workforce

... convene a sharing workshop to reflect on and capture lessons learned. This shouldn't wait until after launch or closeout; it should take place immediately after the team has finished its major effort, while teams are still assembled and while memories are still fresh.”



NASA's Changing Demographics



GN&C Lessons Learned Invited Presentation at ESA/ESTEC

Source: Workforce Information Cubes for NASA (WICN). <http://wicn.nssc.nasa.gov>



Some General Observations on the GN&C Engineering Discipline



Some General Observations on the GN&C Engineering Discipline (1 of 2)



- **The Guidance, Navigation & Control (GN&C) engineering discipline supports all of NASA's Mission Directorates**
- **The GN&C discipline covers a very broad range of engineering & technology activities and specialties related to performing the functions of determining, guiding and controlling the dynamic state of a vehicle as necessary to meet mission objectives**
- **GN&C engineering consists of a wide range of internally interacting and coupled sub-discipline areas**
- **GN&C is very much a system integration discipline with multiple external interactions. Up front work by GN&C Systems Engineers to formulate resilient architectures is critical to mission success**
 - GN&C combines/encompasses aspects of requirements definition, system design, flight hardware, flight software, modeling & simulation, stability analysis, performance analysis, and more



Some General Observations on the GN&C Engineering Discipline (2 of 2)



- **GN&C System Engineering process that tightly couples with Systems Engineering, Flight Mechanics, Avionics (including Communications), Software, Mechanisms, Propulsion, Aerosciences, Loads & Dynamics engineering disciplines**
 - GN&C also has interaction with the Human Factors discipline and Mission Operations for crewed and robotic flight operations command & control applications

- **GN&C involvement on a spaceflight project may be required over the complete “cradle to grave” system lifecycle**
 - GN&C engagement typically spans the range from the initial mission formulation phase through design & development, into flight operations and ending with the mission termination



GN&C Interacts With, and is Influenced by, Virtually All Other Spacecraft Subsystems



"...we cannot do just one thing. Whether we like it or not, whatever we do has multiple effects."

Dietrich Domer, author of the Logic of Failure, commenting on the topic of complex systems

"In space systems, most dynamic problems do not occur in one isolated discipline, but are an interaction between several disciplines or subsystems"

Bob Ryan, author of "Problems Experienced and Envisioned for Dynamical Physical Systems¹", commenting on his Apollo, Skylab, and Space Shuttle career experiences at NASA



GN&C engineers must consistently think at the system-level

¹ NASA Document TP-2508, August 1985



Some Disturbing Recent GN&C Trends



Some Recent Disturbing GN&C Trends



- **Unquantified incremental risk due to reduced testing and reliance on models without anchoring tests**
 - The model is 100% accurate (until we test!)
 - Decreasing testing and reduction in test facility infrastructure on assumption that analytical tools alone are adequate.
- **Flagrant misuse of the “Heritage” term**
 - The most audacious being the claims of “future heritage”
- **Diminished levels of End-to-end closed-loop testing in a Flatsat Hardware-in-the-Loop (HITL) test environment**
- **Piecewise sensor-to-actuator polarity testing**
- **In-flight hardware/software configuration errors**
- **In-flight component failures, in particular reaction wheels**



Some Potential GN&C Pitfalls



An examination of the historical record reveals that several GN&C systems have been seriously victimized by one of more of the pitfalls listed on the following charts either during their design, development, test or operational phases.



Potential GN&C Pitfalls (1 of 2)

- ✓ Poor or Missing GN&C Requirements
- ✓ Failure to Stop Requirements Creep
- ✓ Poor Characterization of Mission Operational Regimes & Environments
- ✓ Unknown or Poorly Defined Interactions
- ✓ Unknown or Poorly Defined Interfaces
- ✓ Poorly Defined Coordinate Frames and System of Units
- ✓ Unknown and/or Incorrectly Modeled Dynamics
- ✓ Feedback Control System Instabilities due to Large Model Uncertainties
- ✓ Reliance on Any “Heritage”: in the Hardware, Software, Design Team, etc.
- ✓ Reliance on low Technology Readiness Level (TRL) GN&C technologies
- ✓ Sensor/Actuator Component Degradation & Failure
- ✓ Insufficient On-Board Processing Capability for GN&C Flight Software (FSW) Algorithms



Potential GN&C Pitfalls (2 of 2)

- ✓ Inadequate Systems Engineering for Coordinated GN&C of Multiple Interacting Vehicles (e.g., during Rendezvous and Docking)
- ✓ Poor GN&C Fault Management Strategy
- ✓ Lack of Comprehensive Abort Strategy
- ✓ Inadequate "Safe Haven" capabilities
- ✓ Failure to "Design for Test"
- ✓ Failure to "Test as You Fly and Fly as You Test"
- ✓ Inadequate Hardware In The Loop (HITL) End-to-End Testing to Verify Proper Operations
- ✓ Inadequate Sensor-to-Actuator Polarity Tests (Lack of End-to-End Testing)
- ✓ Unresolved Test Anomalies & Discrepancies
- ✓ No truly independent Verification and Validation (V & V) process for GN&C
- ✓ Failure to Have Crew and Operations Team "Train as You Fly"
- ✓ Inadequate Validation/Certification of GN&C Ground Data and Tools
- ✓ Insufficient Telemetry for GN&C Performance Monitoring and Anomaly Resolution During Launch, Early Orbit Checkout & All Mission Critical Events



Common GN&C Pitfalls by Project Lifecycle Phase



NASA Life Cycle Phases	FORMULATION			IMPLEMENTATION			
	<i>Pre-Systems</i>	<i>Acquisition</i>	<i>Approval for Implementation</i>	<i>Systems Acquisition</i>	<i>Operations</i>	<i>Decommissioning</i>	
Project Life Cycle Phases	Pre-Phase A: Concept Studies	Phase A: Concept & Technology Development	Phase B: Preliminary Design & Technology Completion	Phase C: Final Design & Fabrication	Phase D: System Assembly, Int & Test, Launch	Phase E: Operations & Sustainment	Phase F: Closeout
• Poor or missing requirements • Requirements creep • Poor characterization of mission operational regimes & environments • Unknown or poorly defined interactions or interfaces • Poorly defined coordinate frames and system of units • Poor GN&C fault management strategy • Lack of comprehensive abort strategy		• Unknown and/or incorrectly modeled dynamics • Feedback control system instability due to large model uncertainties • Reliance on “heritage” hardware, software, design team, etc. • Reliance on low TRL technologies • Inadequate systems engineering for coordinated GN&C during rendezvous and docking of interacting vehicles • Inadequate GN&C “safe haven” capabilities		• Insufficient on-board processing capability for GN&C software algorithms • Unresolved test anomalies & discrepancies • No true IV&V process for GN&C • Failure to have crew and operations team “train as you fly” • Inadequate validation or certification of GN&C ground data and tools • Failure to “design for test” • Failure to “test as you fly and fly as you test” • Inadequate hardware in the loop (HITL) end-to-end testing • Inadequate sensor-to-actuator polarity tests in end-to-end testing		• Sensor/Actuator component degradation & failure • Insufficient telemetry for GN&C performance monitoring and anomaly resolution during launch, early orbit checkout & all mission critical events	



Two Representative GN&C Related Mishap Examples



NASA Dryden Flight Research Center Photo Collection
<http://www.dfrc.nasa.gov/gallery/photo/index.html>

NASA Photo: EC01-0182-11 Date: June 2, 2001 Photo by: Jim Ross

The X-43A/Pegasus combination dropped into the Pacific Ocean after losing control early in the first free-flight attempt.



X-43A / Pegasus Launch June 2, 2001

Ariane 5 Flight 501 June 4, 1996



**NESC's 22 GN&C Best Practices:
15 for “Early Work” and 7 for “Late Work”**



GN&C Best Practices Introduction (1 of 2)



- The NESC completed, in 2007, an in-depth assessment to identify, define and document engineering considerations for the Design, Development, Test and Evaluation (DDT&E) of human-rated spacecraft systems
- Assessment was requested by the Astronaut Office at JSC to help them better understand what is required to ensure safe, robust, and reliable human-rated spacecraft systems. NESC initially studied the NASA Human Spaceflight heritage to identify lessons learned and best practices
- The twenty-two (22) GN&C engineering Best Practices described in this paper are a highly condensed version of what appears in the final NESC Technical Report
 - The first fifteen (15) of these Best Practices apply principally to the early GN&C engineering work associated with **“Architecting the Right System”**
 - The remaining seven (7) Best Practices apply to the later stages of the work which is focused on the end goal of **“Building the System Right”**



Human Spaceflight Heritage: A Significant GN&C Legacy to Study & Learn From



GN&C Lessons Learned Invited Presentation at ESA/ESTEC



GN&C Best Practices Introduction (2 of 2)

- **These Best Practices cover a broad range from fundamental system architectural considerations to more specific aspects (e.g., stability margin recommendations) of GN&C system design and development**
- **Must be emphasized that this initial set of NESC GN&C Best Practices will not be universally applicable “as is” to all projects and mission applications**
- **In addition to examining the GN&C legacy for crewed spacecraft, the NESC assessment team also studied the GN&C lessons learned from several robotic spacecraft mishaps and failures**
- **The team concluded that the engineering Best Practices identified from the study of robotic spacecraft GN&C experiences also apply to the DDT&E of GN&C subsystems for crewed, human-rated, spacecraft**



Motivation for Establishment of the NESC GN&C Best Practices

- Many previously established Lessons Learned must be relearned by the community of practice as organizational memory fades
- The continued repetition of the same GN&C mistakes represents an avoidable risk to crew safety and mission success
- If rigorously followed these GN&C Best Practices will help protect against the pitfalls commonly encountered in the DDT&E process, and will support
 - Increased design consistency,
 - Increased efficiency of the overall DDT&E effort,
 - Increased confidence in the safety and reliability of the human-rated spacecraft's GN&C end product
- Bear in mind however that these GN&C Best Practices will not be universally applicable “as is” to all projects and mission applications

These Best Practices alone are not a substitute for sound engineering judgment, experience, expertise, attention to day-to-day details, and intellectual curiosity.



Purpose of the NESC GN&C Best Practices

- **Objective is to offer useful guidance, in the form of these Best Practices, to the design, development, test and operation of GN&C systems for NASA's future spacecraft.**
- **The GN&C Best Practice information is also intended to provide:**
 - Insights for non-GN&C engineers and managers
 - Tutorial-type guidance for fresh-out GN&C engineers
 - A useful memory aid for more experienced GN&C engineers especially as a checklist for technical evaluation and review of a GN&C system.
- **Beyond simply sharing these NESC GN&C Best Practices a secondary motivation of this talk is to invite feedback on this initial set of best practices from the ESA GN&C engineering Community of Practice (CoP)**
 - Are there other specific GN&C Lessons Learned from the ESA GN&C CoP derived from their flight system and technology development project experiences?



List of the NESC 15 Early Work GN&C Best Practices



- 1** Early and iterative GN&C subsystem architectural development
- 2** Define all GN&C interdisciplinary interactions and relationships
- 3** Ensure implementation of comprehensive Abort/Safe Haven strategies/functions
- 4** Adequacy of host computer and proper selection of execution frequencies
- 5** Independent hardware and software for GN&C fault management
- 6** Establish & flowdown GN&C requirements for multi-vehicle system
- 7** Evaluate redundancy with identical GN&C hardware components
- 8** Evaluate heritage hardware and software in the GN&C architecture
- 9** Make certain that new GN&C technology is well qualified
- 10** “Design for Test” when evaluating candidate GN&C architectures
- 11** Define and document the coordinate frames and the system of units
- 12** Controller designs shall have robust stability margins
- 13** Understand & completely analyze the dynamics in ALL flight phases
- 14** All test anomalies must be understood and may need to be included in the truth model
- 15** Verification Truth Model must be developed independently



List of the NESC 7 Late Work GN&C Best Practices



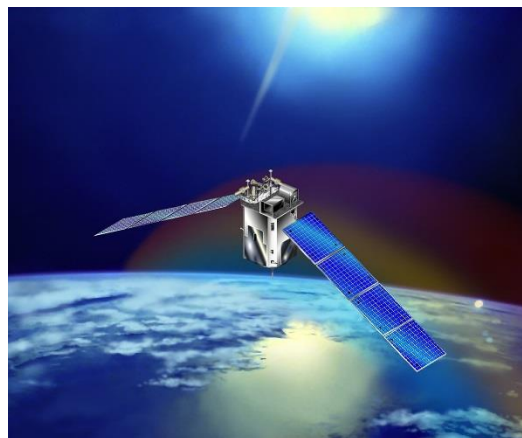
- 16** Establish a strong relationship with, and maintain close surveillance of GN&C lower-tier component-level suppliers
- 17** Adhere to the “Test As You Fly” philosophy
- 18** Conduct true end-to-end sensors-to-actuators polarity tests in all flight configurations
- 19** Plan and conduct sufficient GN&C hardware-in-the-loop testing to verify proper interactions
- 20** Carefully manage GN&C ground databases, uploads, ground application tools, and command scripts / files
- 21** Ensure sufficiency of GN&C engineering telemetry data
- 22** “Train as They Fly”: Develop a dedicated real-time GN&C simulator for the crew/operators



Discussion of Best Practices vs. Real-World Mishaps



NASA Dryden Flight Research Center Photo Collection
<http://www.dfrc.nasa.gov/gallery/photos/index.html>
NASA Photo: EC01-0182-11 Date: June 2, 2001 Photo by: Jim Ross
The X-43/Pegasus combination dropped into the Pacific Ocean after losing control early in the first free-flight attempt.





Top-Level Summary of the LEWIS Mishap



LEWIS was launched on August 23, 1997 into low Earth Orbit.

- 1. At launch, LEWIS was under control of the A-side processor. At first contact it had already switched to the B-side and was unable to playback SSR data.**
- 2. After 45 hours of nadir pointing on B-side, the Ground crew switched control back to the A-side. The attitude was uncontrolled so the A-side Sun pointing mode was entered.**
- 3. After verifying that the spacecraft had been stable in the Sun mode for four hours of operation, the Ground crew entered a nine-hour rest period and ceased operations for the day.**
- 4. During that unattended period, the spacecraft entered a flat spin that resulted in a loss of solar power and a fatal battery discharge. Contact with the spacecraft was lost on Aug. 26.**
- 5. The spacecraft re-entered the atmosphere and was destroyed on 28 September 1997.**





Root Causes of the LEWIS Mishap vs. NESC GN&C Best Practices



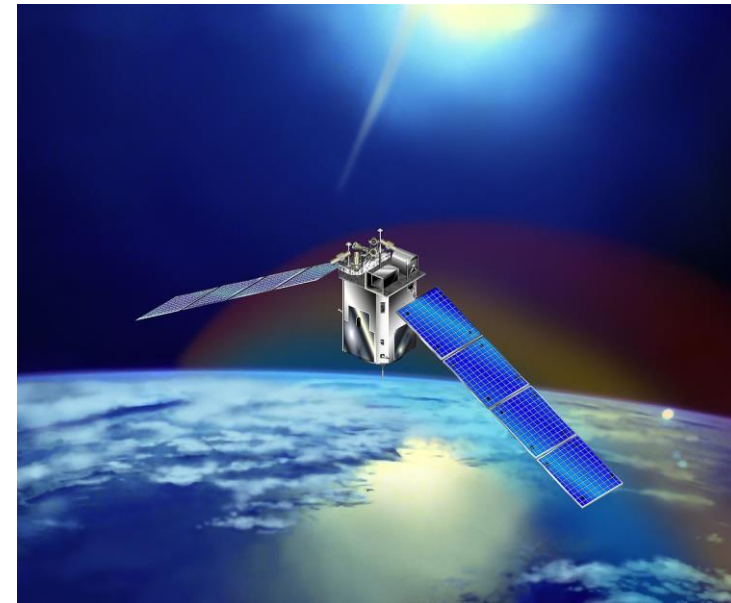
1. Safe mode was adapted from the TOMS space-craft which had its X-axis normal to the solar array. X was the major axis of inertia on TOMS but it was the intermediate axis of inertia on Lewis.
BP #8: Over-reliance/Over-Confidence on TOMS heritage.
BP #1: GN&C Safe mode architectural was not iterated.
2. X-axis spin rate was not sensed and could not be controlled.
BP #3: Ensure implementation of comprehensive Abort/Safe Haven strategies/functions.
3. The Ground crew failed to adequately monitor spacecraft health and safety during the critical initial mission phase.
BP #21: Ensure sufficiency of GN&C engineering telemetry data.
4. X-axis rate produced disturbance torques in other axes resulting in excessive thruster firings which led to autonomous shutdown of thrusters.
BP #13: Understand & completely analyze the dynamics in ALL flight phases.
5. In the absence of control, the spacecraft dynamics transferred spin from the X to the Z axis with the solar array edge on to the Sun.
BP #15: Independent Truth Model should have identified un-modeled effects.



Top-Level Summary of the TIMED Mishap

The Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) spacecraft was launched on 7 December 2001 into low Earth orbit. There were 4 separate GN&C anomalies early in the mission:

1. Shortly after separation there was a steady increase in spacecraft system momentum.
2. Coming out of eclipse and seeing the Sun for the first time in Sun Pointing Mode, the spacecraft pointed an incorrect axis toward the Sun.
3. The Nadir Pointing Mode, which is used for Science observations, had an unanticipated 2.1 Hz oscillation.
4. Momentum dumping occurred 10 times/day rather than the expected once/day.





Root Causes of the TIMED Mishap vs. NESC GN&C Best Practices



1. There was a Sign Error in the Momentum Unloading Control Logic.
BP #18: True end-to-end sensors-to-actuators polarity tests not conducted.
2. Two of the Sun Sensors were not in the flight configuration during ACS polarity test.
BP #17: "Test As You Fly" philosophy was not enforced.
3. There was a Controls-Structures Interaction (CSI) with the Solar Array Flex Mode which varied from 2.0-2.6 Hz depending on array orientation.
BP #2: Interactions between GN&C, Power, and Structures were not well defined.
BP #12: Stability margins were not robust to parameter variations.
4. The Spacecraft had a 10 A-m² Residual Magnetic Dipole.
BP #2: Residual dipole requirement was not specified.
BP #17: Residual dipole was not measured in ground test.

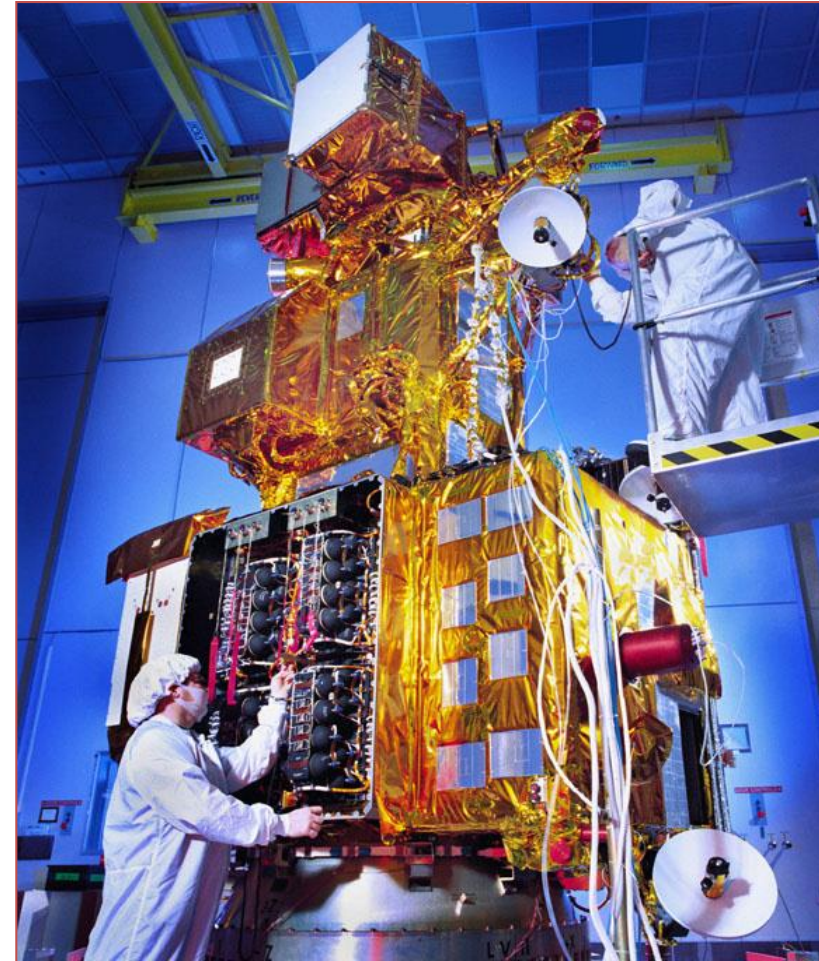




Top-Level Summary of Landsat-6 Failure (1 of 2)



- Landsat-6 Was 6th spacecraft in Landsat series of Earth remote-sensing satellites dating back to 1972
- Spacecraft design based on DMSP (military) & TIROS (civilian) meteorological satellite heritage. Significant departure from L4 & L5 heritage
- STAR-37XFP apogee kick motor (AKM) used for post-separation ΔV to attain 705-km circular polar mission orbit (DMSP/TIROS heritage)
- 4 100-lbf-thrust reaction engine assembly (REA) hydrazine thrusters would fire to counteract disturbance torques generated by AKM firing
- Entire ascent phase planned to take 40 min., then Ascent Guidance would “hand over” spacecraft control to orbit mode





Top-Level Summary of Landsat-6 Failure (2 of 2)



- Launched Oct. 5, 1993, on 2-stage Titan-II booster from VAFB
- Throughout ascent phase, Titan-II telemetry was nominal
- No Landsat-6 spacecraft real-time telemetry available during ascent due to S-band frequency conflict with Titan-II
- Titan-II telemetry data indicated spacecraft separation from booster occurred at nominal time/place
- Anticipated 1st post-launch ground station contact with L6 never established
- Subsequent attempts to search for & acquire spacecraft signals were futile
- Reports from other assets indicating reentry events downrange from observed Titan-II booster stage reentry events
- Conclusion: L6 spacecraft had not achieved orbit following Titan-II separation
- Total mission loss



Landsat-6 Failure Analysis (cont.)



- **L6 spacecraft experienced rupture in reaction control subsystem (RCS) hydrazine manifold**
- **Rupture caused by explosive detonation of hydrazine**
 - Water hammer effect after firing of normally closed pyrovalve #1
 - Hydrazine preset on both sides of pyrovalve #2 prior to activation
 - Hot gas blow-by when normally closed pyrovalve #2 fires 1 sec. after pyrovalve #1
- **Ruptured hydrazine manifold rendered spacecraft's REAs useless; propellant could not reach engines**
- **Without stabilizing attitude control torques from REAs, spacecraft tumbled uncontrollably during AKM burn**
- **Consequently spacecraft did not accumulate sufficient ΔV (energy) from AKM firing to attain Earth orbit**
- **L6 spacecraft re-entered atmosphere south of equator approximately 30 min. after liftoff**



Lessons Learned from Landsat-6 Failure



- **Modifications to DMSP/TIROS RCS subsystem heritage design not fully appreciated at system level**
 - Common view across project of the RCS as a low-risk “heritage” implementation
- **Limited modeling & test of RCS subsystem**
- **RCS subsystem engineering lacked continuity due to several programmatic starts & stops**
- **Lack of L6 spacecraft telemetry for monitoring critical launch & ascent events**



Top-Level Summary of the X-43A Mishap



The HXLV (Pegasus) was used to accelerate the Hyper-X Research Vehicle (HXRV) to the required Mach number and operational altitude for demonstration.

- The trajectory that was selected to achieve the mission was at a lower altitude (i.e. a higher dynamic pressure) than a typical Pegasus trajectory.
- Flight went as planned after B-52 drop until pitch-up maneuver.
- Diverging roll oscillation at 2.5-Hz frequency occurred during pitch-up.
- Roll oscillation continued to diverge until about 13 seconds into flight.
- Rudder electro-mechanical actuator stalled & ceased to respond to autopilot at that point causing loss of yaw control.
- Loss of yaw control caused X-43A stack sideslip to diverge rapidly to over 8°.
- Structural overload of starboard elevon occurred at 13.5 sec.
- Loss of control caused X-43A stack to deviate significantly from planned trajectory.
- Vehicle terminated by range control about 49 sec. after release.





Root Causes of the X-43A Mishap vs. NESC GN&C Best Practices



1. The vehicle control system design was deficient for the trajectory flown due to inaccurate analytical models which overestimated design margins.
BP #8: Over-reliance/Over-Confidence on Pegasus heritage.
BP #17: Failure to adhere to “Test as You Fly” approach.
2. Failure triggered by divergent roll oscillatory motion at 2.5 Hz, caused by excessive control system gain.
BP #12: Insufficient control system stability margins.
3. Modeling inaccuracies in fin actuation system & aerodynamics. Insufficient variations of modeling parameters.
BP #13: Lacking parametric uncertainty analysis for control system.
4. Rudder actuator stall occurred as consequence of divergent roll which accelerated loss of control.
BP #14: Inadequate dynamic modeling.
5. Flight failure was only reproduced when all modeling inaccuracies with uncertainty variations were incorporated in system-level linear analysis model & nonlinear simulation model.
BP #15: Independent Truth Model should have identified un-modeled effects.



Lessons Learned from Conestoga



- The maiden flight of the Conestoga 1620 launch vehicle occurring on October 23, 1995 at NASA's Wallops Flight Facility (WFF).
- This resulted in a complete failure, with the vehicle going out of control at T+46 seconds at an altitude of 6 nm during first stage powered flight

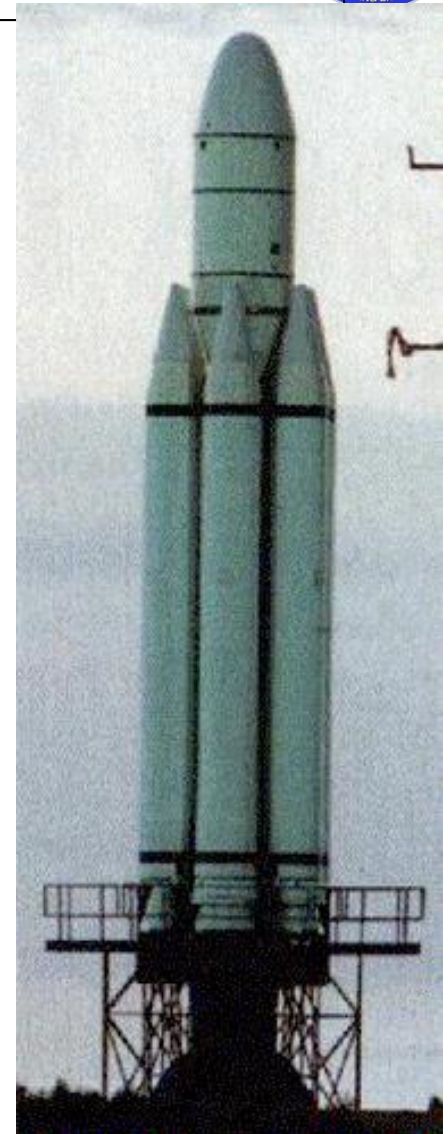




Lessons Learned from Conestoga



- The Conestoga 1620 launch vehicle first stage consisted of a Castor 4A solid motor core, with six additional Castor 'strap-on' motors arranged symmetrically around the core.
- The set of six strap-on motors consisted of four Castor 4B solid motors with steerable nozzles plus two fixed nozzle Castor 4A solid motors.
- A modern-control theory-based Linear Quadratic Regulator (LQR) controller was used to generate, at a 25 Hz cycle rate, Thrust Vector Control (TVC) nozzle steering commands to the Castor 4B motors.
- The LQR controller approach was adopted after an earlier classical-control theory-based Proportional, Integral and Derivative (PID) TVC control law design proved unable to handle the task of stabilizing the multiple flexible mode of the launch vehicle structure.
- Inertial sensor feedback was used to stabilize and control the pitch axis and yaw axis attitude.

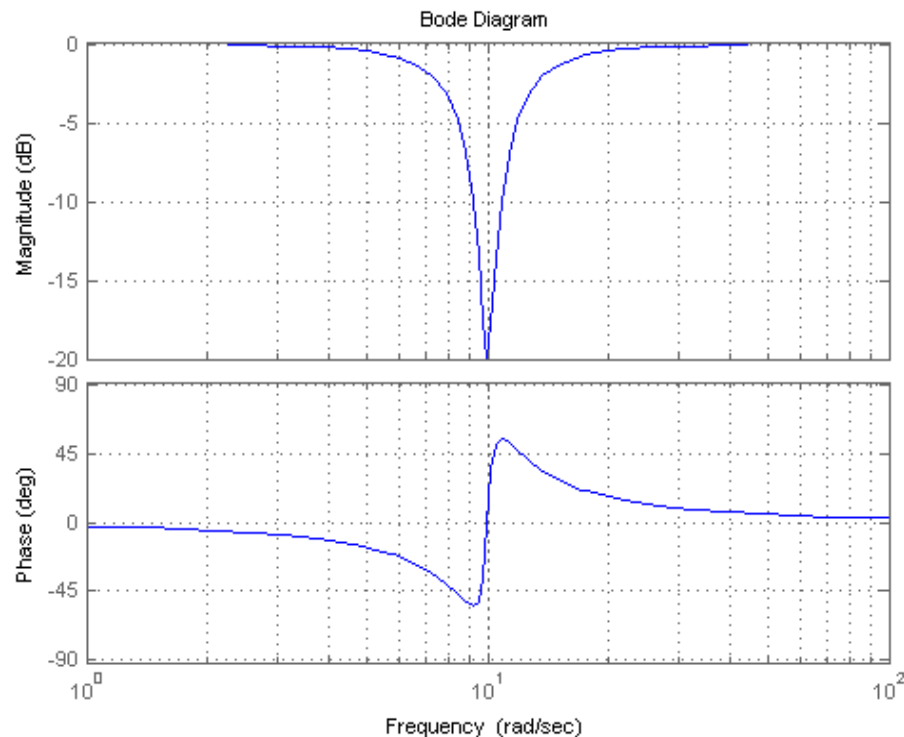




Lessons Learned from Conestoga



- The Conestoga TVC FCS designers chose to employ a notch structural mode filter in their loop compensation.
- This notch filter was designed to deeply attenuate the effects of the launch vehicle's first structural mode present in the gyroscope feedback signal to the TVC control law.
- The center frequency of the notch filter design was set at approximately 4 Hz
- This was the frequency region where the structural Finite Element Model (FEM) predicted several closely-spaced vehicle structural modes to occur



**Generic Notch Filter,
centered at 10Hz**



Validation of the Conestoga FEM?



- The Conestoga flight control system designer requested test-validated modal frequency, mode shape and modal damping data to properly design the notch filter for the TVC control system
- A relatively costly and time-consuming 'hang and twang' type modal test was proposed in which the vehicle would be hung in air, in order to approximate the free-free boundary conditions experienced in flight
- Instead a Ground Vibration Test (GVT) was performed on the Conestoga launch vehicle prior to launch while it was mounted on its launch pedestal
- The results of this GVT were then in turn used to validate the vehicle structure FEM.
- The free-free boundary conditions were adjusted in the FEM mathematical model to reflect the clamped-free GVT configuration
- A reasonably close match in flexible mode frequency was accomplished for only the first bending mode
- Beyond the first bending mode, the agreement between the FEM prediction and the GVT test data deteriorated significantly.



Conestoga Failure Analysis Results



- Post-failure telemetry analysis revealed the Stage 1 motor TVC nozzle actuators were significantly ‘over-cycled’ starting shortly after liftoff in response to the TVC commands resulting in depletion of the finite reservoir of actuator hydraulic fluid
- The failure investigation team pinpointed the source of the actuator over-cycling as an unanticipated low-frequency structural vibration mode that was not adequately filtered out by the 4 Hz notch filter in the TVC control loop
- This unanticipated low-frequency mode was a torsional mode of the vehicle physically caused by the joint compliances between the strap-on Castor motors and the core vehicle
- The FEM of the launch vehicle structure significantly underestimated the first torsional mode of the system. The analysis of the ascent telemetry revealed the first torsional flexible mode was approximately 6.2 Hz, as opposed to the 4 Hz center frequency of the notch filter





Lessons Learned from Conestoga



Conestoga LL #1

Perform a Sensitivity Analysis of Notch Structural Mode Filter Performance: Notch filtering approaches for loop stabilization should be undertaken with great care and attention to modal data uncertainty. If using a notch filter, determine what the appropriate modal data accuracy tolerance is for the mission application at hand. Determine the sensitivity to uncertainty in the bending mode frequency, mode shape and mode damping.

Conestoga LL #2

Systems Engineering is Vitrally Important to Mission Success: The System Engineering team should set the requirements for a Project's modeling and simulation activities. For example, they should ensure FEMs are properly test-validated. System Engineering should understand the interplay between the GN&C and Structures disciplines, particularly in the area of controls-structures interaction.

Conestoga LL #3

Define the Requirements for a Ground Vibration Test to Validate the Launch Vehicle Structural FEM: Define the requirements for FEM modal-prediction accuracy and determine the type of GVT need to support FEM model validation.

Conestoga LL #4

If Developing a Unique First-of-a-Kind Vehicle Structure, Perform Multiple Independent Structural Modeling and Analysis Cycles: Recognize and fully appreciate the technical challenges of modeling vehicles with a significantly different non-heritage type structural configuration. Anchor these structural modeling and analysis cycles with modal data from a GVT.



Top-Level Summary of the ARIANE-5 Flight 501 Mishap



The maiden flight of the Ariane 5 launcher on June 4, 1996 relied on identical GN&C hardware and software for redundancy.

- 39 seconds into the flight the primary Inertial Reference Unit (SRI-1) stopped sending correct attitude data due to a software exception.
- The OBC switched to the backup unit, but SRI-2 also failed due to its independently determined software exception.
- The OBC could not switch back to SRI-1 so it took data that was actually part of a diagnostic message written to the bus by SRI-2. This data was interpreted as flight data and used for thrust vector control.
- The sudden swivelling of both solid booster nozzles up to the limit caused the launcher to tilt sharply giving rise to intense aerodynamic loads leading to destruction of the vehicle.





Root Causes of the ARIANE-5 Flight 501 Mishap vs. NESC GN&C Best Practices



1. Primary Inertial Reference Unit, SRI-1, stopped sending correct attitude data due to a software exception.
 - BP #2: *Interactions between S/W and GN&C were not defined with enough care.***
 - BP #8: *Heritage software for Ariane-4 was inappropriate for Ariane-5.***
 - BP #20: *Database confusion over reference trajectories.***
 - BP #17: *Failure to adhere to “Test as You Fly” approach.***
2. Switchover to the backup unit was accomplished, but SRI-2 immediately failed in the same way as SRI-1.
 - BP # 7: *Evaluate if redundancy using identical GN&C components increases or decreases reliability.***
3. The OBC could not switch back to SRI-1 so it accepted SRI-2 diagnostic data as attitude data and generated improper TVC commands.
 - BP #3: *Ensure that Abort/Safe Haven strategies/functions are properly implemented. Ariane-5 was lacking a simple and reliable “Never Give Up” flight control capability.***



Some Key GN&C System Considerations for Human-Rated Spacecraft



Significant GN&C Related Anomalies on Crewed Spacecraft



STS-9 Nov 1983
Landing delayed due to 2
GPC failures and an IMU

STS-91 June 1991
Primary Avionics Software
System (PASS) corrupted
by GPS errors

Apollo 10 May 1969
LM tumbles while in low
lunar orbit; IMU gimbal lock
narrowly avoided during
attitude recovery by crew

Apollo 11 July 1969
LM guidance computer
overloads during powered
descent

Skylab Nov 1973
Control Moment Gyro
(CMG) failure

Gemini 8 March 1966
Failed "On" thruster causes
vehicle to tumble; crew uses re-
entry thrusters to recover attitude



Progress M-7 March 1991
Aborted Progress docking leads to
near-miss encounter with Mir space
station due to Kurs radar damage

Soyuz TM-17 Jan 1994
Collides twice with Mir



Apollo 14 Feb 1971
Faulty LM abort mode
switch delays landing six
hours

ISS June 2002
Control Moment Gyro
(CMG) failure

ISS June 2007
Loss of thruster based
attitude control due to
Russian computer outage

Progress M-34 June 1997
Collides with Mir

Apollo 16 April 1972
CM IMU gimbal lock anomaly occurs, platform
automatically enters to "Coarse Align" mode,
the crew accomplishes manual platform
realignment using Sun and Moon references

STS-1 April 1981
Unmodeled vernier thruster
plume impingement causes
greatly increased duty cycles
and propellant consumption

STS-3 March 1982
Dynamic interaction between Orbiter
flight control system and robotic arm
motion causes unexpectedly high
vernier thruster duty cycles

STS-1 April 1981
Significant unpredicted
Orbiter rocking motion on
ET, when SSME's slewed to
stow position, dynamic
interaction causes cyclic
pitch thruster firings

STS ALT-5 October 1977
Approaching runway Enterprise enters into a
PIO along both pitch and roll axes due to
270-millisecond time delay in the Fly-By-
Wire flight control system, problem later
corrected with a suppression filter

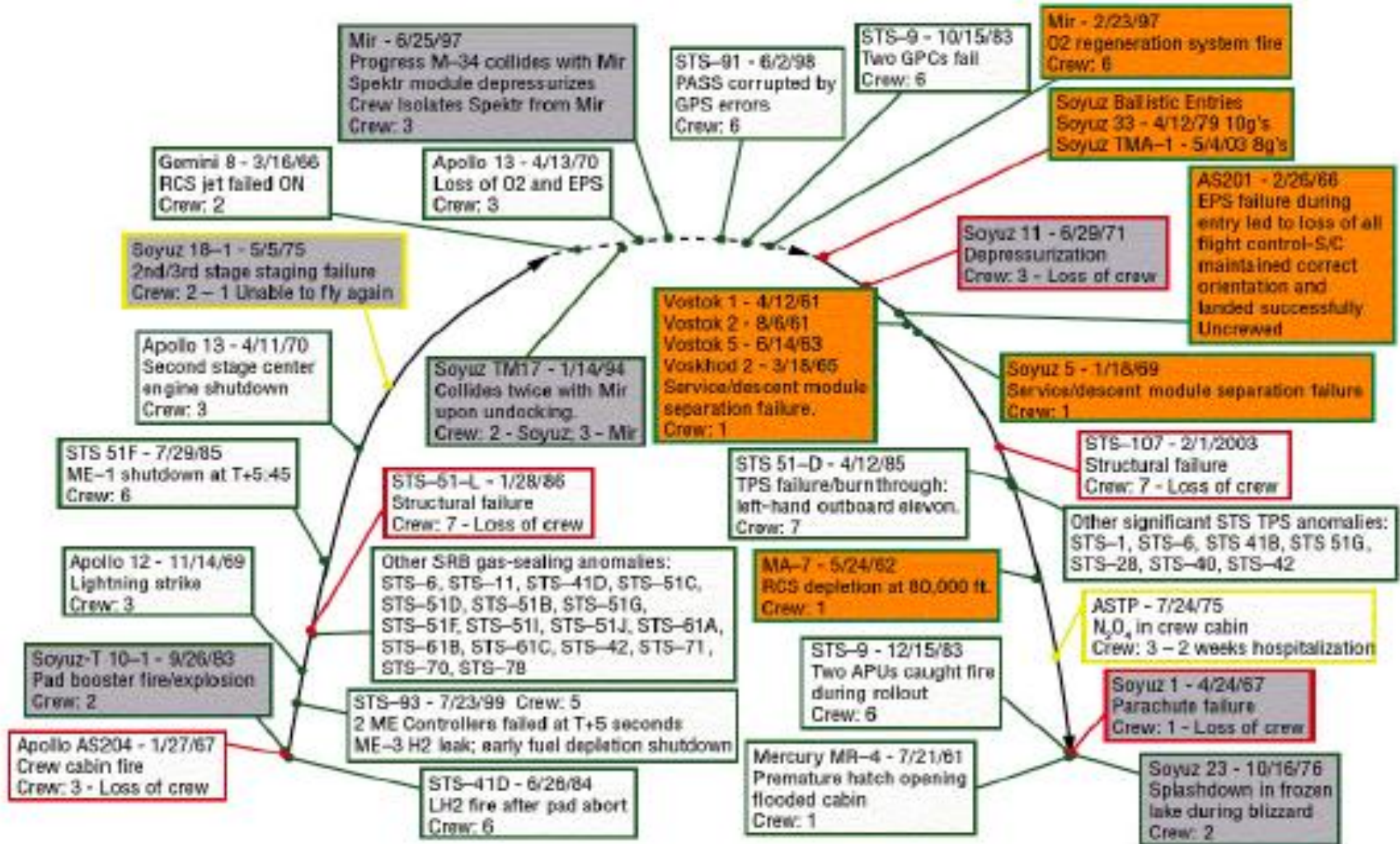


STS-3 March 1982
Handling Qualities (PIO)
problem occurs; causes
unintended Orbiter pitch-
up during landing rollout





Significant Human Space Flight Vehicle Failures





Some Observations on Significant Human Space Flight Vehicle Failures



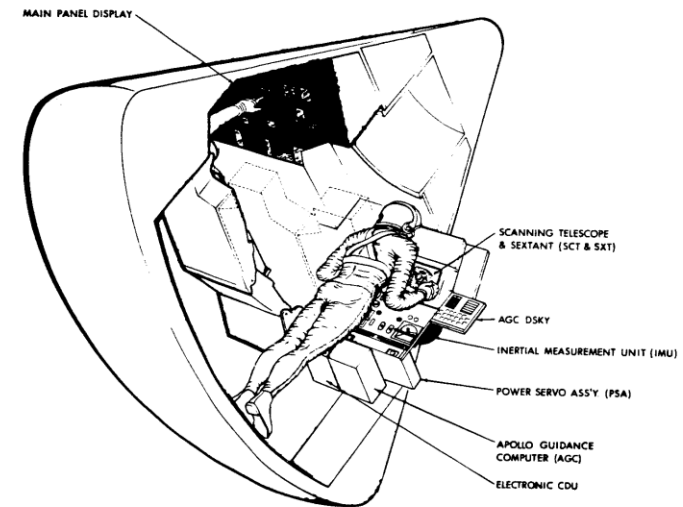
- **The proceeding figure shows all known human spaceflight failures, catastrophic and significant, as a function of relative mission timeline**
 - Red Outline Box: Loss of crew
 - Yellow or Orange: Crew health threatened
 - Green Outline Box: Significant event or close call/crew unaffected
 - Grey Box Shading: Russian space flight missions
- **Failures can occur at any time and that significant failures have occurred on-orbit**
- **Relatively few GN&C-related human spaceflight failures/mishaps/anomalies:**
 - Gemini 8 RCS “on” thruster anomaly (1966)
 - STS-9 IMU failure (1983)
 - Soyuz collision with Mir (1994)
 - Progress M-34 collision with Mir (1997)
 - STS-91 GPS errors (1998)
- **In failure cases other than ascent and reentry the crew had time evaluate, troubleshoot, and respond to on-orbit failures (e.g., Apollo 13)**
- **It can be inferred that spacecraft robustness precluded a number of significant failures from becoming catastrophic**
- **One notable statistic: With the exception of the Apollo-1 cabin fire, the loss of human life has only occurred during ascent and reentry which are the two most dynamic phases of the mission**
- **During high risk/highly dynamic mission phases it is important to include response time and automation into the redundancy and backup spacecraft reliability trades**
- **The different aspects of all mission phases must be considered when selecting spacecraft architectures and when deciding where to buy down risks**



Some Key GN&C System Considerations for Human-Rated Spacecraft



- **Take time to properly architect the GN&C System(s)**
 - Directly impacts crew safety, mission success, upgradeability & Life Cycle costs
 - Flowdown requirements for Rendezvous, Proximity Operations, Docking and Undocking (RPODU)
 - Carefully consider redundancy using identical vs. diverse H/W and S/W components
- **Minimize complexity where possible**
 - Impacts reliability, testability, and operability, as well as any potential vehicle GN&C commonality
- **Have robust abort strategies and reliable Safe-Haven capabilities**
 - Absolutely need a simple “Never Give Up” Safe Haven mode able to return crew safely to Earth
- **Carefully evaluate the cost/benefit trade for heritage hardware and software**
 - Recall Shuttle experience with tactical aircraft inertial systems, GPS receivers, and processors
- **“Train as You Fly”**
 - Factor in early the crew feedback on GN&C architecture, human-machine interface, and operational procedures



Flight-Like Cockpit Mockups (such as MIT/IL Apollo Hybrid Simulator) Allowed Apollo Astronauts Hands-On Training Which Influenced the GN&C Design



7 Fundamental Elements of a Solid Flight Rationale



7 Fundamental Elements of a Solid Flight Rationale (1 of 2)



In 2005, for the STS-114 Return to Flight (RTF), the engineers came up with seven steps, which were baselined in the Shuttle Program, as the way to approve technical issues for flight—the so-called Seven Elements of Flight Rationale.

“These are good, solid systems engineering-type questions that you ask whenever there’s an issue that comes up where something’s not acting the way it was designed to.”

– Bryan O’Connor (former NASA Chief of Safety and Mission Assurance)



7 Fundamental Elements of a Solid Flight Rationale (1 of 2)



RSRM CULTURE

7- ELEMENTS OF GOOD FLIGHT RATIONALE

DENNIS MOORE



- ◆ **Solid technical understanding**
 - Physics based or root cause understanding of issue, based on engineering data (perhaps using a fault tree)
- ◆ **Condition relative to experience base**
 - Experience base includes full-scale flight, ground test, or qualification level tests
- ◆ **Bounding case established**
 - Using physics based understanding, determine the bounding case (e.g., lower A-basis allowables, upper three sigma loads and environments, anchored with test data)
- ◆ **Self limiting aspects**
 - Physical reasons why it can't get any worse than the bounding case or show the part is fail-safe
- ◆ **Margins understood**
 - Adequate margins, ideally not substantially reduced from baseline
- ◆ **Assessment based on data, testing and analysis**
 - Final risk assessment based on test data and analysis, not gut feel or expert opinion
- ◆ **Interactions with other elements/conditions addressed**
 - Address interactions with other conditions (MRB, changes, technical issues), and vehicle elements

Implemented 2001





NESC Academy



NESC Academy



- The NESC Academy captures the experience of the NESC experts and passes that experience along to NASA's next generation
 - Formal, classroom-based discipline courses developed from 2005 – 2008.
- Academy has evolved to a web-based multimedia format where each NESC discipline team has opportunity to develop and present discipline-specific topics, case studies, and lessons-learned.
 - Over 85 videos covering discipline-specific topics, NESC Assessments, and other NESC presentations presently available from the NESC Academy Online (www.nescacademy.nasa.gov)
 - Over 70 of these lessons are discipline specific, originating from the Technical Fellow TDTs.
 - Webcast lessons can be formulated, broadcast and archived by the NESC Academy.



NESC Academy Online
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David M. Schuster
NASA Technical Fellow

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CFD-Guided Prediction of Launch Vehicle Aeroacoustics	Craig Street	58 Minutes 16 Seconds
Lessons Learned on Past Manned Spaceflight Programs That Seem to Have Been Forgotten	Bass Redd	52 Minutes 4 Seconds
X-38 First Flight	Steve Labbe	20 Minutes 22 Seconds
Ares Aerodynamic Testing and Lessons Learned	Bill Tomek	24 Minutes 9 Seconds
Flying the World's Fastest Airplane: The Hyper-X / X43A Story	Walt Engelund	1 Hour 7 Minutes 1 Second
NASA Computational Aeroelastic Analyses for the Ares Vehicles	Robert Bartels	25 Minutes 34 Seconds



“Fundamentals of GN&C”

Engineering Discipline Webcast Events

(Some Examples)



**Fundamentals of
Kalman Filtering and Estimation
(Dr. Christopher D'Souza, JSC)
March 2013**



**Fundamentals of
Deep Space Navigation
(Dr. Shyamkumar Bhaskaran, JPL)
September 2015**



**Fundamentals of
Planetary Tour Design
(Aron Wolf, JPL)
August 2015**



**Fundamentals of Spacecraft
Handling Qualities
(Dr. Karl Bilimoria, ARC)
January 2012**



**Fundamentals of Adaptive Control
(Dr. Irene Gregory, LaRC)
November 2012**



**Fundamentals of
Control-Structure Interaction
(Dr. Davin Swanson,
The Aerospace Corporation)
March 2017**

GN&C Lessons Learned Invited Presentation at ESA/ESTEC



Concluding Remarks



Concluding Remarks

- **The timely capturing and sharing of knowledge across the Agency is not “nice to do” — it is a “must do” responsibility for NASA engineers and our industry partners.**
- **We should look back to make sure we have comprehensively captured lessons from the past; this is especially important given the current demographics of NASA as our senior engineers retire**
- **Every GN&C engineering organization should have a Lessons Learned system**
- **In a learning organization individual engineers must take it upon themselves to seek out, study, and share key GN&C lessons learned**
- **We need to find ways to embed the recurring lessons in NASA design & development policies/processes as well in discipline-specific Recommended Best Practices guideline documents.**



Backup Charts