Expanding Humanity’s Frontiers of Discovery

- **Initial Exploration Missions**
  - Space Launch System
  - Multi-Purpose Crew Vehicle
  - 21st Century Ground Operations

- **Gaining the High Ground**
  - Cis-Lunar Space
  - Geostationary Orbit
  - High-Earth Orbit
  - Lunar Flyby & Orbit
  - Lunar Surface

- **Into the Solar System**
  - Interplanetary Space
  - Initial Near-Earth Asteroid Missions

- **Exploring Other Worlds**
  - Low-Gravity Bodies
  - Full-Capability Near-Earth Asteroid Missions
  - Phobos/Deimos

- **Planetary Exploration**
  - Mars
  - Solar System

Key:
- **Objective**
  - Missions

- **Surface Capabilities Needed**
- **Advanced Propulsion Needed**
- **High Thrust In-Space Propulsion Needed**

National Aeronautics and Space Administration
A Brief History of the Marshall Space Flight Center (MSFC)

Extensive Experience with Systems Engineering and Integration

- Huntsville’s Army team uses a Jupiter-C rocket to launch Explorer I, America’s first satellite. (1958)
- Saturn Test Firing at MSFC (1964)
- Apollo-Soyuz Test Project (1975)
- Lunar Roving Vehicle (LRV) driven on moon. (1971)
- First Spacelab Mission (STS-9) (1983)
- Hubble Launched (1990)
- ISS Assembly Begins (1998)
- New Horizons to Pluto launched (2006)
- Space Launch System (Planned 2017)

**1960**
- Shepard’s Flight Aboard MSFC Tested Redstone Rocket (1961)
- MSFC Established Dr. Wernher Von Braun, First Director (1960)

**1970**
- Skylab (1973)
- Apollo 11 (1969)

**1980**
- STS-1 is launched (1981)
- Solid Rocket Motor Re-Design (1987)
- ASTRO-1 was launched aboard the Space Shuttle Orbiter Columbia (STS-35) (1990)

**1990**
- Chandra was launched July 23, 1999 aboard the Space Shuttle Columbia STS-93 mission (1999)
- First Spacelab Mission (STS-9) (1983)

**2000**
- Stardust returns comet dust to Earth (2006)

**2010**
- FASTAT (2010)

**2011**
- Space Shuttle Final Flight STS-135 (2011)
- Space Launch System (Planned 2017)
Aerospace Systems Became Complex by 1940s–60s

- 1940s: B-29, V-2, Corporal, P-80, P-86
- 1950s: Ballistic Missiles (Atlas, Titan, Polaris, Jupiter, Minuteman), Spacecraft (Explorers and Pioneers), and Aircraft (B-36, B-52, F-104)
- 1960s: Aircraft (F-111), Spacecraft (Mercury, Gemini, Apollo, Ranger, Mariner)

Sample Drivers

- Most vehicles don’t return from space; those that do must be even more reliable
- Extreme temperatures, pressures, vibration loads
- Heterogeneous technologies (structures, mechanical, electronics, computing, control, rocket propulsion)
- High, concentrated energy (rocket propulsion, reentry)
- Zero gravity (floating particles)
- Autonomy (classical Guidance, Navigation, and Control (GN&C), command sequencing, failure management)

Complex Defined as “Beyond a Single Person’s Understanding”
**Systems Integration: Genesis in Failure**

- **Greater than 50% Failure Rates**
- **Primary Causes**
  - Mismatches between design-to-build and as-flown configuration
  - Vibration damage
  - Debris/contamination
- **Systems management/integration**
  - Developed by U.S. Air Force (USAF) and U.S. Army, Jet Propulsion Laboratory (JPL), and Army Ballistic Missile Agency (ABMA) in 1950s-60s for ballistic missiles and early spacecraft
  - Bernard Schriever (WDD, Ballistic Missile Division)
  - George Mueller (NASA Apollo)
  - Simon Ramo (Ramo-Wooldridge)
  - Samuel Phillips (Minuteman)
  - Jack James (JPL)
  - Wernher von Braun (ABMA, MSFC)

*By Mid-1960s, Failure Rates Decreased to Less Than 10%*

“Surely, general, you can give us a better answer for all the recent missile failures besides, ‘that’s how the cookie crumbles’!!”

*Samuel Phillips Papers*
*Library of Congress*
Systems Management / Integration

♦ **Project Management – Manager’s Approach**
  • Heavy pre-planning: System does not return, must build it right the first time, cannot fly and return prototypes (as with aircraft)
  • Organize by product instead of by discipline

♦ **Systems Analysis – Scientist’s Approach**
  • Developed from operations research; assess technical feasibility, design, and operational alternatives

♦ **Systems Engineering – Engineer’s Approach**
  • Configuration control, coordinate diverse subsystem technologies

♦ **Configuration Management**
  • Key link between management hierarchy and engineering working groups
  • Developed at Boeing for Minuteman (Sam Phillips)
  • Ties cost and schedule to engineering changes
  • Design reviews tied to “change freeze and baseline” process

♦ **Environmental and System Testing + Reliability and Quality Assurance Methods**

*Various Methodologies for the Same End Game: Mission Success*
Systems Integration: Consistency Theory in Practice
Human Space Flight Values Complexity and Gigantism

- Crew capsule systems are complex and heavy
- Launch vehicles tend toward gigantic proportions
  - Safely lift the crew capsule in the event of an early engine shutdown or other launch emergency
  - Substantial energy necessary to get out of Earth’s gravity well and to achieve a sustainable orbit
  - Launch vehicles tend to be more mass efficient when staged

Mass Drives Cost and Size
### Spectrum of United States Launch Vehicles

#### Sample of Proposed and Fielded Systems

<table>
<thead>
<tr>
<th>Small</th>
<th>Medium/Intermediate</th>
<th>Heavy</th>
<th>Super Heavy</th>
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<tbody>
<tr>
<td>XCOR Lynx</td>
<td>AFRL RBX Pathfinder</td>
<td>Orbital AA-2</td>
<td>ATK Athena II C</td>
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<tr>
<td>Masten XA-1.0</td>
<td>NESC MLAS</td>
<td>Orbital Minotaur IV &amp; V</td>
<td>Orbital Taurus I &amp; II</td>
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<td>NASA Nova Concept</td>
<td>NASA Saturn V</td>
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<td>NASA HLV</td>
<td>4/8/2011 21st CGSP</td>
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</tbody>
</table>

National Aeronautics and Space Administration
System Context: The Guiding Principle of Systems Integration

- Understanding the System Context is essential to a coherent integration approach
- Maintaining System Integration within the System Context is essential to efficient system life cycle execution
  - Apple’s computers have successfully followed a basic paradigm over the past 30 years
  - The original principles of the Macintosh are embodied in today’s computers as they were in the original 1984 model
    - Simple user interaction and operation guide the implementation and integration of Apple applications
    - Apple products provide an ever increasing set of complex functions, yet within the same basic System Context and Systems Integration model

Images from http://en.wikipedia.org/wiki/Macintosh
Image from Apple Inc.: http://www.apple.com/

Systems Integration Is Specific to the System Being Integrated
Understanding Context:
Cost is a Function of Performance

♦ Extreme requirements drive the cost 318%

♦ Question: Is a 14% increase in maximum speed (performance) worth 318% increase in cost?

♦ Question: Is a 34% increase in 0 – 60 mph (performance) worth 318% increase in cost?

Porsche 911 Carrera
- Cylinders: 6
- Engine layout: Rear
- Performance: 180 mph
- 0-60 mph: 4.7 sec
- MSRP: $77,800
- Horsepower: 345

Porsche 911 Turbo
- Cylinders: 6
- Engine layout: Rear
- Performance: 195 mph
- 0-60 mph: 3.5 sec
- MSRP: $160,700
- Horsepower: 530

Porsche 911 GT2 RS
- Cylinders: 6
- Engine layout: Rear
- Performance: 205 mph
- 0-60 mph: 3.4 sec
- MSRP: $245,000
- Horsepower: 620

System Context Drives Decisions
Payload to Orbit Cost Trends

Commercial Space Vehicles Costs Are Lower

Government Launch Vehicles Costs Are Higher

Mass to Orbit (pounds) vs. Cost per Pound to Orbit

- Pegasus
- Delta
- Titan
- H 2A
- Ariane
- Atlas
- Shuttle
- Proton

National Aeronautics and Space Administration
System Context Provides Direction for Systems Integration

- **Uses**
  - Human Transport
  - Science Missions
  - Resupply
- **Operations**
  - Autonomous
  - Manual
  - Human/System Interaction
  - On-Board Operations
  - Fixed-Base Operations
- **Environments**
  - Low-Earth Orbit
  - Interplanetary Space
- **System Context sets**
  - Interfaces and Interface Constraints
  - Algorithm and Software Integration
  - Operations Integration
  - Integrated Test and Verification Set

The System’s Use Is Critical to Delivering the Right Product for the Purpose
Systems Integration and System Architecture

Systems Integration involves defining the System Architecture
- Distribution of Functionality
  - System Elements
- Distribution of Operations
  - Ground Based/On-board
  - Automated/Manual
- Definition of Assembly Process

System Architecture involves various aspects
- Durability – The system should function robustly and remain in good condition
- Utility – The system should be useful and function well for the users
- Beauty – The system should delight stakeholders and raise their spirits
- Based on architectural concepts of Vitruvius
  (http://penelope.uchicago.edu/Thayer/E/Roman/Texts/Vitruvius/home.html)

Robustness (durability and utility) of the concept provides ease of handling integration issues
- Cost Margins
- Cost Reserves
- Performance Margins

System Architecture Most Clearly Embodies “Form Follows Function”
(Louis Sullivan: http://www.prairiestyles.com/lswilliam.htm)
Driving in Complexity: The Path to Extinction

Why the Neanderthals Became Extinct

Yes, but Og assured me that this will improve our efficiency and keep us ahead of those Cro-Magnons in the valley.
System Integration must stay focused on fostering simplicity in the system interactions, interfaces, and operations

- System Integration can easily drive complexity into any system interaction, interface, or operation
- Apple provides very robust applications integrated through block upgrades
  - iPod => iTouch => iPhone => iPad

  - Each product release incorporates new capabilities that expand and improve user applications and interactions, built on familiar foundations that came before

Block Upgrades provide an approach to manage increasing system functionality and cost, and provides

- An opportunity for the system to stay focused on a few simple integration activities rather than diverse and complex integration activities
- An opportunity for off-ramps of the system or of system functions as experience is gained with system use and operation
- Manageable steps to increase system functionality over time
  - Timely initial release
  - More robust functionality in subsequent blocks

Images from Apple Inc.: http://www.apple.com/
Beautiful Systems Appropriately Integrate Functions

Every Group Has Their View Of The System. The Integrator Must See the Whole, With Each Facet Appropriately Incorporated.
Stability of System Concept

♦ System Concept must be consistent
  • Technically
  • Financially
  • Schedule

♦ System Concept must be persistent
  • The concept cannot change with time or circumstance
    – Changes involve a redefinition of the system and the
      system expectations = a New System

♦ System Integration is dependent on sustaining the system concept through the development and operations phases

Systems That Are Consistent and Persistent Are Stable
Effective communication is essential to integration

- All groups (Design, Test, Operations, Maintenance) must be working to the same objectives in the same context

- Multiple, uncoordinated approaches lead to multiple solutions to the same question or challenge
  - The source of the greatest defeat of system simplicity
  - Greatly increases integration complexity

- Groups working different aspects of a solution must be maintained in sync
  - Communication is the key, not process
    - Process facilitates communication, but will not maintain sync by itself
    - Communication pathways should be simple
      - Organizational stove pipes inhibit communication and must be explicitly managed
      - Functional swim lanes help clarify responsibility and must be actively managed to avoid becoming barriers to communication
  - Communication is personal
Summary

♦ System Integration was refined through the complexity and early failures experienced in rocket flight

♦ System Integration encompasses many different viewpoints of the system development

♦ System Integration must ensure consistency in development and operations activities

♦ Human Space Flight tends toward large, complex systems

♦ Understanding the system’s operational and use context is the guiding principle for System Integration
  • Sizeable costs can be driven into systems by not fully understanding context
  • Adhering to the system context throughout the system’s life cycle is essential to maintaining efficient System Integration

♦ System Integration exists within the System Architecture

♦ Beautiful systems are simple in use and operation
  • Block upgrades facilitate manageable steps in functionality evolution

♦ Effective System Integration requires a stable system concept

♦ Communication is essential to system simplicity
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New National Capability

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Economic Prosperity
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Technology Development
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