John F. Kennedy Space Center

LAUNCH SERVICES PROGRAM

High Technology Systems with Low Technology Failures

Some Experience with Rockets on Software Quality & Integration

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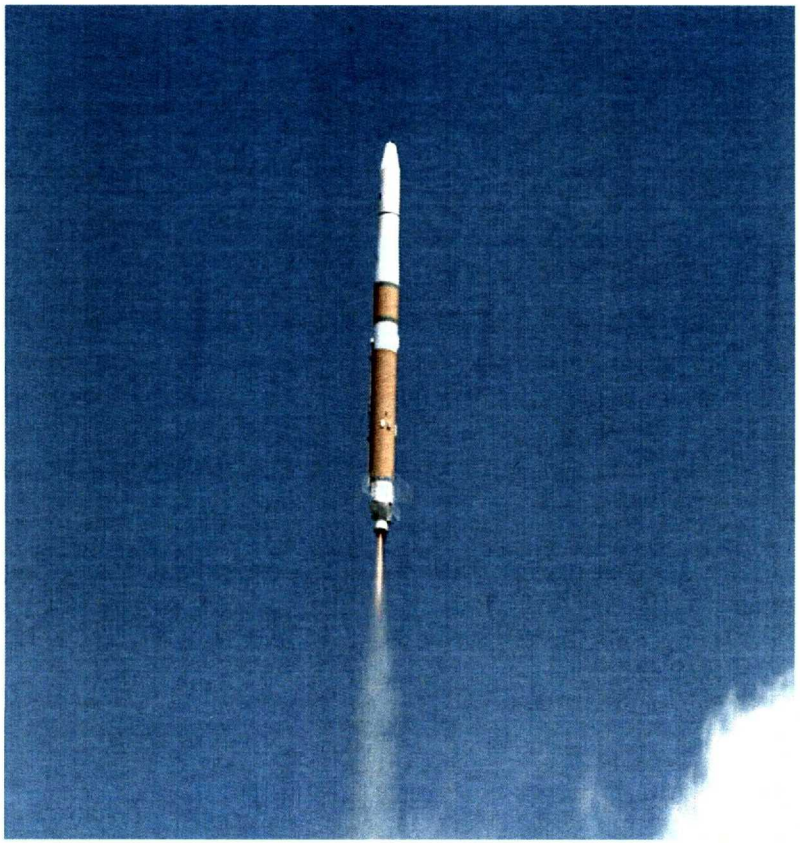
Launch Vehicles (aka Rockets)

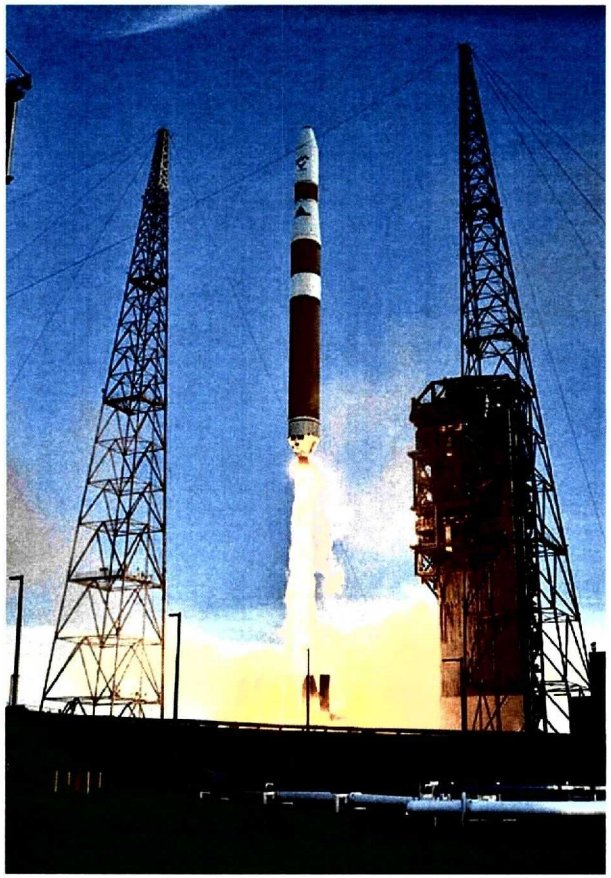
Background

- What is a launch vehicle (rocket) and what is it supposed to do?
  - A system which provides a spacecraft with the correct velocity and position at the correct time to be in the desired orbit
  - It just keeps adding velocity by accelerating until it gets to the desired orbit velocity
- Where did rockets come from?
  - The Chinese invented gunpowder and put it in bamboo tubes for essentially fireworks for festivals in about the 1st century AD
- Why did this technology not advance very far until the 20th century AD?
  - Inertial Guidance which consists of Navigation, Guidance & Control
  - This is the major functionality difference which separates model rockets from real rockets

Model Rockets vs. Real Rockets



Model Rockets
$5.00 - $200.00



Real Rockets
$30 M - $500 M

What is Navigation, Guidance & Control

- Navigation – Where am I?
- Guidance – What is the path I want to take to get to where I want to go?
- Control – How do I keep on the path to get there?

- The invention of the accelerometer and gyroscopes allowed us to measure the value and direction of acceleration

- Numerically integrate acceleration and you get velocity
- Numerically integrate again and you get position
- If you know where you started you can guide to your desired end point

- BUT it took a computer to perform the numerical computations

Quiz

Question #1

What do you get when you cross a computer with a battleship?

Question #2

What do you get when you cross a computer with a camera?

Question#3

What do you get when you cross a computer with an automobile

Question #4

What do you get when you cross a computer with a rocket?

System Aspects

- Anytime you introduce computer technology into an engineered system you inherit the failure modes of the computer including software

- What is a system?
  - A construct or collection of different elements that together produce results not obtainable by the elements alone
  - Rockets have system requirements to accomplish their function as a system

- What is quality?
  - Conformance to requirements (does it work at the system level?)
  - Sometimes confused with luxury which is the presence or absence of certain product requirements or features

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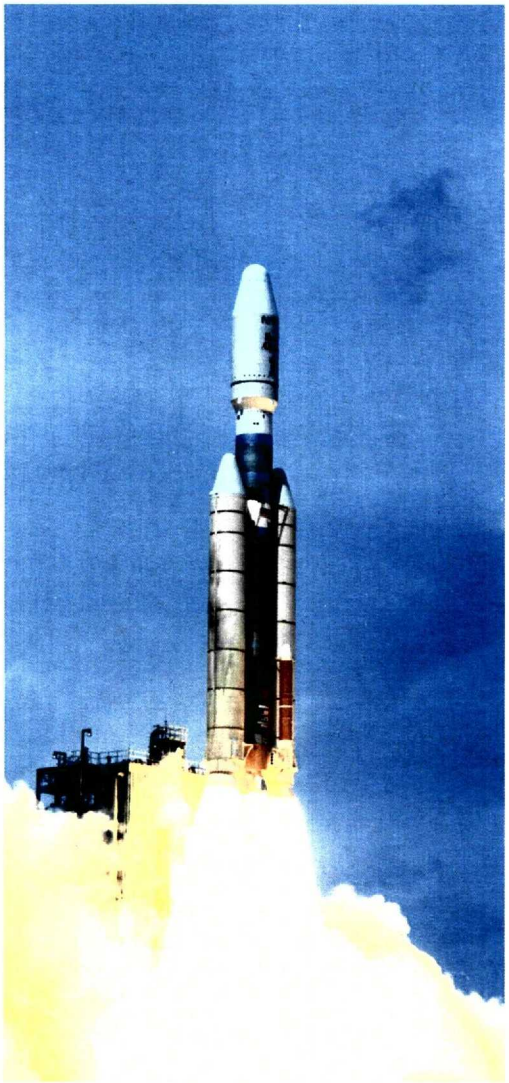
History of Rocket Failure Causes

- **Early Flights**
  - Design & Environment Errors
- **More Recent Flights**
  - Undetected processing errors (damaged systems)
  - Systems integration errors (systems do not play together like they should)
  - Collateral damage (propagated failures in complex systems)
- **Some Rather Notable Failure Case Studies in Rocket Software Integration**
  - Commercial Titan 3 Flight 2 (CT 2)
  - Ariane 5 Flight 1 (501)
  - Titan IV Centaur Flight 14 (TC 14)

Commercial Titan 3 Launch Vehicle

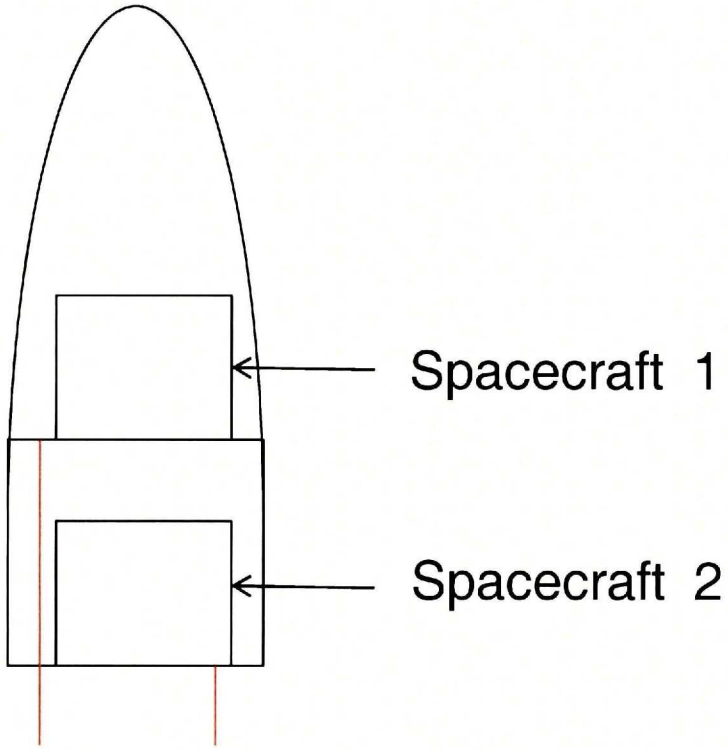


Commercial Titan 3 Flight 2 (CT 2)

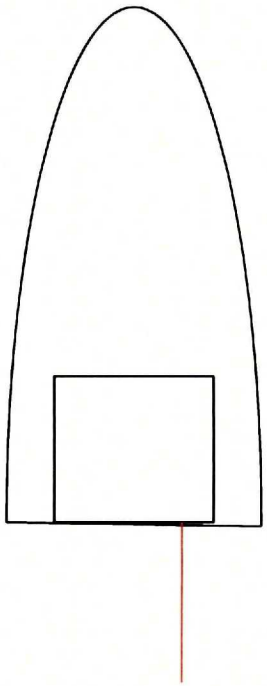
- Commercial Version Modification of DoD/NASA Titan
  - Intended to compete in the commercial communication satellite market
  - Single and Dual Spacecraft Payload Configurations
- First Flight was a Dual Payload Configuration
  - Successfully Injected and Separated the Skynet 4A & JCSAT2 payloads on December 31, 1989
- Second Flight was a Single Payload Configuration
  - Failed to Separate the Single INTELSAT 603 Payload when commanded when launched on March 14, 1990
  - $265 M Loss (Uninsured $150 M Payload)
- Incorrect Software/Electrical Configuration when switching from Dual to Single Payload Configuration
  - Inadequate testing to detect the design error
- CT 3rd flight with the same INTELSAT 6 payload was a success

Commercial Titan 3 Payload Configurations

Dual Payload Configuration

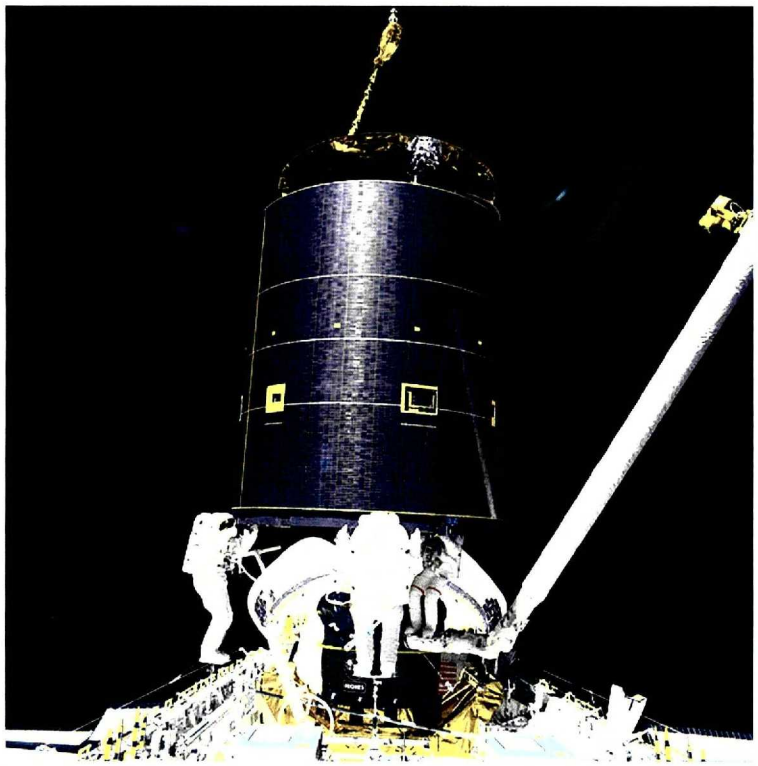


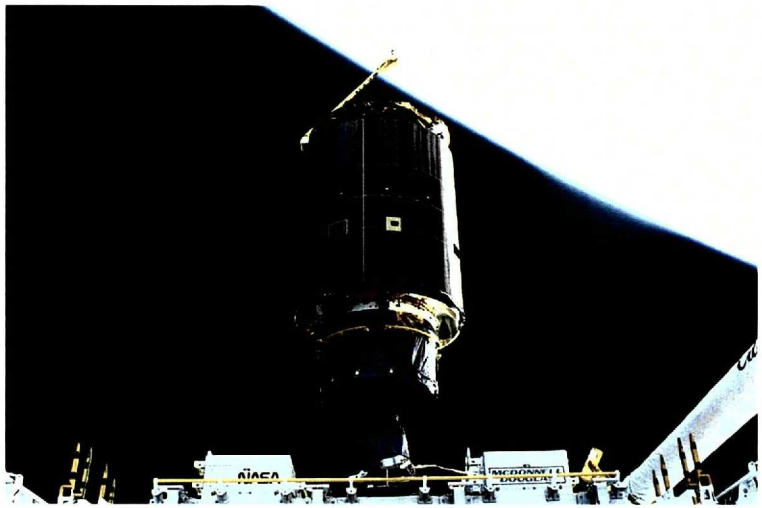
Single Payload Configuration



Separation Command Wire Harnesses

The Rest of the INTELSAT 603 Story





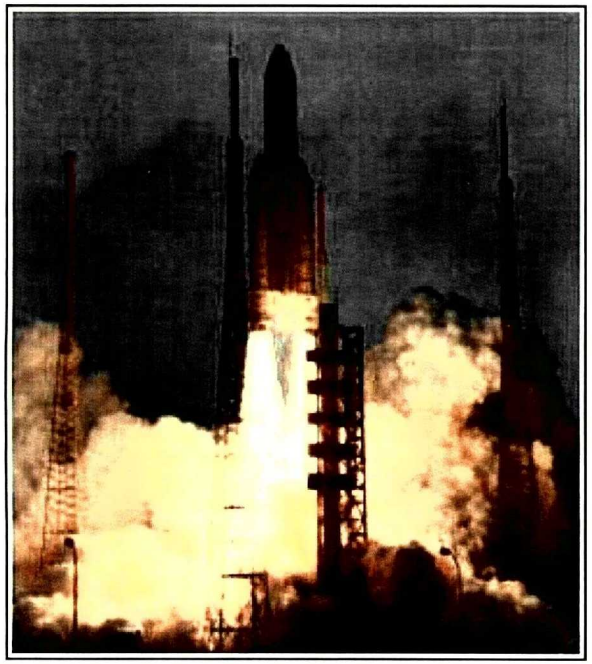
STS - 49 Retrieval Mission

Ariane 5 Launch Vehicle

Ariane 501

- First Flight of a major upgrade from Ariane 4 to Ariane 5
  - Addition of large solid rocket boosters
  - Intended to capture a large share of the commercial communication satellite launch market
  - $ 7 Billion development program
  - Launched on June 4, 1996
- 37 seconds after engine ignition the vehicle abruptly changed attitude, broke apart due to aerodynamic forces and initiated the vehicle flight termination system
  - $370 M Loss
- Control system sent an unneeded major attitude change signal to the engine control actuators
- Guidance system sent erroneous data to the control system due to a shutdown of the inertial measurement unit (IMU) computer

Ariane 501 Flight



Liftoff !

37 seconds later !!!

What happened to Ariane 501?

- Data transmitted from the IMU was not proper flight measurement data but was a diagnostic bit pattern of the IMU computer which was interpreted as flight data
- The IMU computer had declared a failure due to a software exception
- The internal IMU software exception was caused during execution of a data conversion from 64 bit floating point to a 16 bit signed integer value
  - The floating point number which was converted had a value greater than what could be represented by a 16 bit signed integer
  - Related to a horizontal velocity measurement
  - Resulted in an Operand Error
- The data conversion instructions in Ada code were not protected from causing an Operand Error

What happened to Ariane 501? (cont)

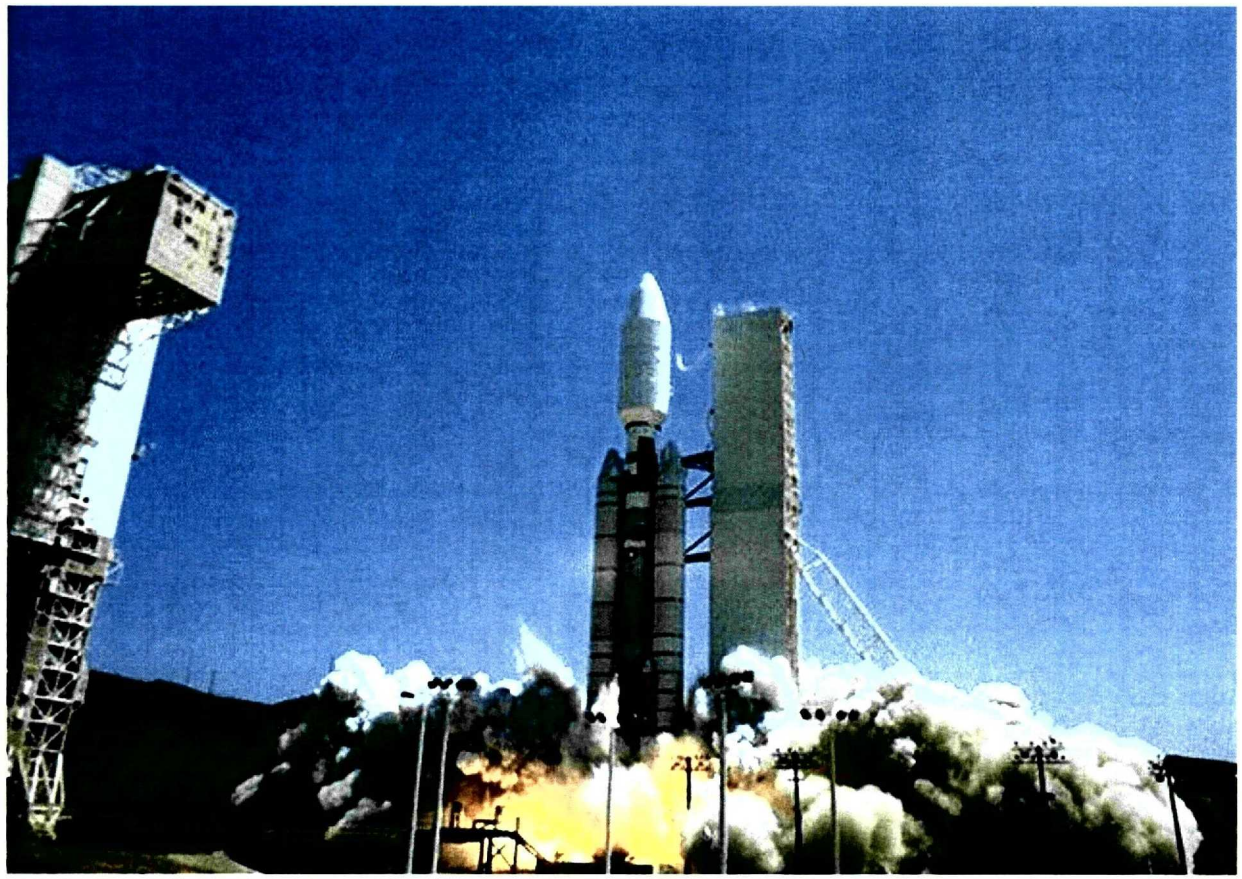
- The exception handling mechanism for the IMU computer was
  - The failure was to be indicated on the databus
  - Failure context stored in EEPROM
  - Processor shut down
- Attempted to switch to a redundant IMU processor
  - Could not do so because the redundant IMU processor had failed during the previous data cycle for the same reason
- Error occurred during in a part of the software which is used for strap down inertial platform alignment
  - Provides meaningful results only prior to liftoff
  - After liftoff this function serves no purpose
- The alignment function was operative for 47 sec after liftoff
  - Time sequence was based on requirements for Ariane 4 and was not required for Ariane 5 (Reuse/commonality of software)
  - Used for rapid realignment of IMU on Ariane 4

What happened to Ariane 501? (cont)

- The Operand Error occurred due to an unexpected high value of a variable called horizontal bias
  - Related to sensed horizontal velocity
  - Horizontal velocity value for Ariane 5 was about 5 times the value for Ariane 4

- IMU System was not tested with the simulated Ariane 5 trajectory
  - IMU specification did not contain the Ariane 5 trajectory as a functional requirement
  - When they did so the failure was duplicated
  - IMU specifications did not indicate operational restrictions

Titan IV Centaur Launch Vehicle



Titan IV Centaur Flight 14

- Titan IV Centaur is a US launch vehicle used for DoD & NASA missions
- Launched on April 30, 1999
- Upper stage (Centaur) tumbled out of control after spinning itself at a value an order of magnitude too high
  - Spacecraft placed in useless orbit
  - Due to an incorrect roll sensor gain software parameter value off by an order of magnitude (or one decimal place)
  - $ 1 Billion Payload Loss (Uninsured US Air Force payload)
- Roll is motion about the longitudinal axis of a rocket
  - Occurs while sitting on the earth due to earth rotation
- Incorrect software value could have been detected in prelaunch testing data analysis
  - In specification but out of family

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Failure Mitigation Strategies

- Practice Systems Engineering
  - Know how everything works as a system
  - Have domain knowledge of functionality/criticality
  - In a control system everything matters (sensors, computation, actuators and their data)
  - Software has imbedded assumptions in its logic
- Think about what can go wrong
  - Success is eliminating/mitigating causes of failure
  - Maybe use some formal failure analysis techniques
    - » FMECA, Event Sequence Diagrams
  - Think about how to make systems robust
  - Study technology history and learn from others mistakes
- Devise simple sanity tests/data analysis to eliminate errors
  - Think functionality
  - Analyze the data
  - Isolate one function at a time

Failure Mitigation Strategies (cont)

- Testing
  - Tests to prove no possibility of a negative function
  - Graceful degradation/failure handling
  - Try to break the software
- Progressive levels of integration testing
  - Elements may work by themselves but not together
- End to End and Integrated Testing
  - Test Like You Fly
  - Fly Like You Test
- Random Hardware Failures are Rare
  - Design, Integration, Testing & Data Analysis Failures are NOT