Keeping Models Current

Aging Surveillance of Solid Rocket Motors

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RSLP Charter

- TASC Launch and Missile Programs Organization includes the Rocket System Launch Program(RSLP)
  - Provides Mission Assurance and Systems Engineering to USAF for applications using retired Minuteman II and Peacekeeper Weapon System Hardware
  - Legacy is from the TRW Ballistic Missiles Division dating back to the 1960's.
- RSLP Engineering Center performs independent analyses and technical reviews; monitors processing and testing of GFE motors; and conducts post-flight analyses

Launch and Missile Programs History

- 15 consecutive successful launches of new vehicle configurations:

  - STARBIRD
  - LCLV
  - TCMP-I
  - TCMP-II
  - ait-1
  - ait-2
  - NTW/QRLV
  - MSLS
  - Minotaur I
  - Minotaur II/TLV
  - LRALT
  - MRT
  - NFIRE TLV
  - Juno
  - Minotaur IV

...With 3 different launch vehicle contractors

  - Orbital
  - Lockheed Martin
  - Coleman Aerospace

.... From 8 different Ranges

  - Wallops
  - Cape Canaveral
  - Wake
  - Vandenberg
  - Kodiak
  - PMRF
  - RTS
  - White Sands

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Source of Motors

- Solid Rocket Motors used for US ICBM fleet since early 1960's
  - High reliability
  - Low Maintenance
  - Rapid Response
- Minuteman (MM) II motors deactivated in early 1990's when Peacekeeper was fielded
- Peacekeeper (PK) motors decommissioned in the 2004's
- Aging Surveillance (A/S) program in place during deployment to track trends and spot degradation
  - Design life of motors approximately 5-10 years
- Motors stored for future use
  - A/S program taken over by Space Development and Test Directorate
  - Motors are currently well beyond design life but continue to show high reliability

Maintaining Reliability of Decommissioned Motors

- Motors which are aging beyond current operational service life estimates (SLE) are monitored under RSLP A/S program
  - Identify materials and/or components as age critical
  - Evaluate age related trends, providing sufficient response time to react to aging concerns
  - Maintains confidence in the continued safety of storage and existing reliability estimates for the motor designs
  - Conducted on a motor-by-motor basis
- Data collected from the A/S program is used to establish meaningful useful life estimates of the propulsion, ordnance and component sub-systems

Trend Analysis

- For RSLP, the term *useful life estimate* (ULE) has been added to differentiate from SLE as defined by the operational program.
  - An engineering review and statistical analysis of A/S measured data is performed to identify any significant aging trends and develop the ULEs

- Trend Analysis Life Estimate (TALE) – Probability of failure versus time when materials and components designated as age critical show an aging trend
  - Measured property versus storage time is assumed to be linear
  - Linear analysis predictions are evaluated against age
    - Additional analysis performed as required

Aging Trends

- Determining aging trends
  - Least-squares fit applied to a linear aging model:

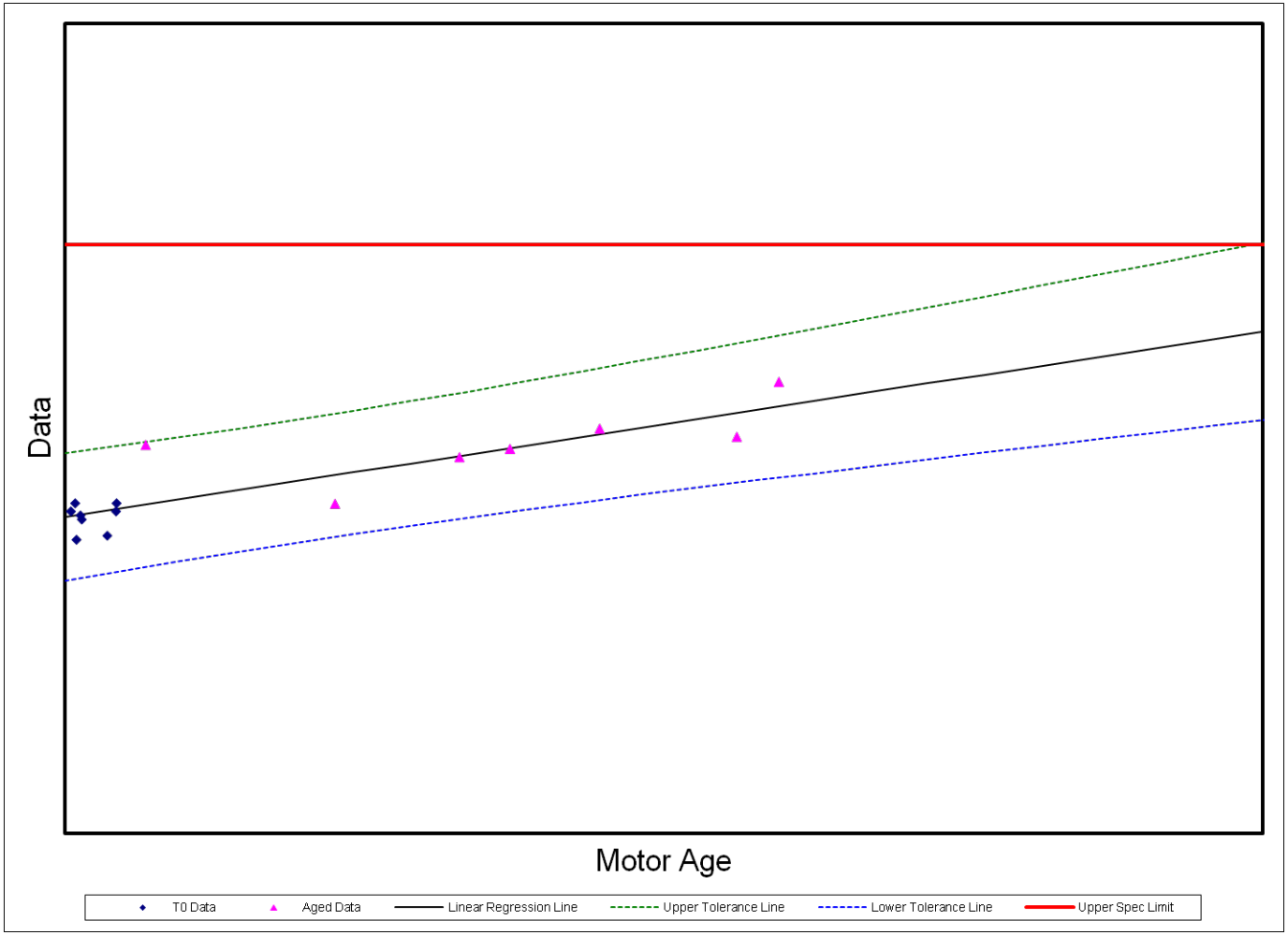
$$P = K(age) + P_0$$

  - P is any property, K is an aging rate and P_0 is the value of the property at zero age
  - K and P_0 constants are calculated by least squares fitting the data

- Determining whether the trend is age related
  - A significance level (p-value) less than or equal to a given threshold is used to indicate an aging trend

TALE - Sample

- TALE based on intersection between tolerance line and specification value



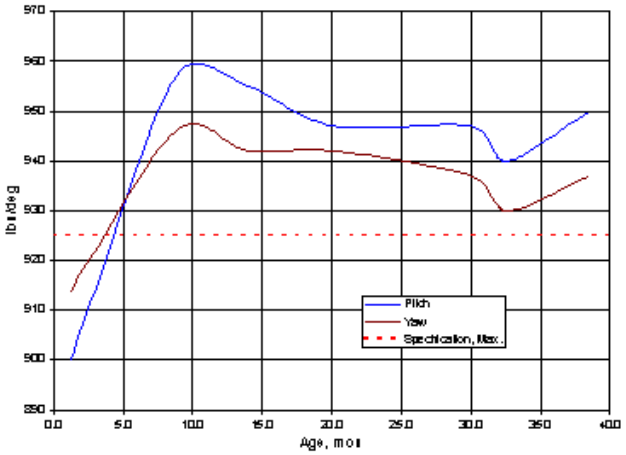
Aging Effects

- Propellant hardness (modulus) increases may lead to cracking of the grain
  - High-rate strain capability
- Propellant/Liner/Insulation (PLI) bondline strength (tensile and shear) may degrade allowing for separation, resulting in overpressurization / case burn through which could lead to case structural failure
  - Excise samples
    - Chemical tests: Gel-Filler Fraction (GFF) and Swelling Ratio (SR)
    - Mechanical tests: Propellant/insulation stress relaxation; propellant uniaxial tensile (bondline & bore); constant rate tensile (bondline)
  - Motor dissection
- Soft goods (o-rings, greases, etc.)
  - Hardening of o-rings may lead to leakage and result in hardware structural failure

Flexseal Aging

- Non-linear model defines the predicted dynamic operation of the actuator control loop interacting with the nozzle and flexseal assembly:
  - Slew Rate
  - Spring Rate
  - Gain and Phase response of actuator assemblies
  - Actuator force
  - Flexseal torque
    - Modified based on flexseal age
- Physical
  - Post curing of the rubber material (hardening)
- Response
  - Flexseal spring-rate (lbs/deg) increase from acceptance test value

Spring-Rate @0.9 Pressure Ratio
Force vs. Angle



A/S Data Impacts on Mission Assurance

- A/S data used to keep models current for mission assurance IV&V analysis
- Models data updated by A/S data affects analyses across all the disciplines either directly or via their interactions with other analysis
  - Avionics analysis
  - Dynamics and test
  - GN&C analysis
  - Propulsion analysis
  - Software analysis
  - Structures analysis
- A/S data directly used in GN&C analysis

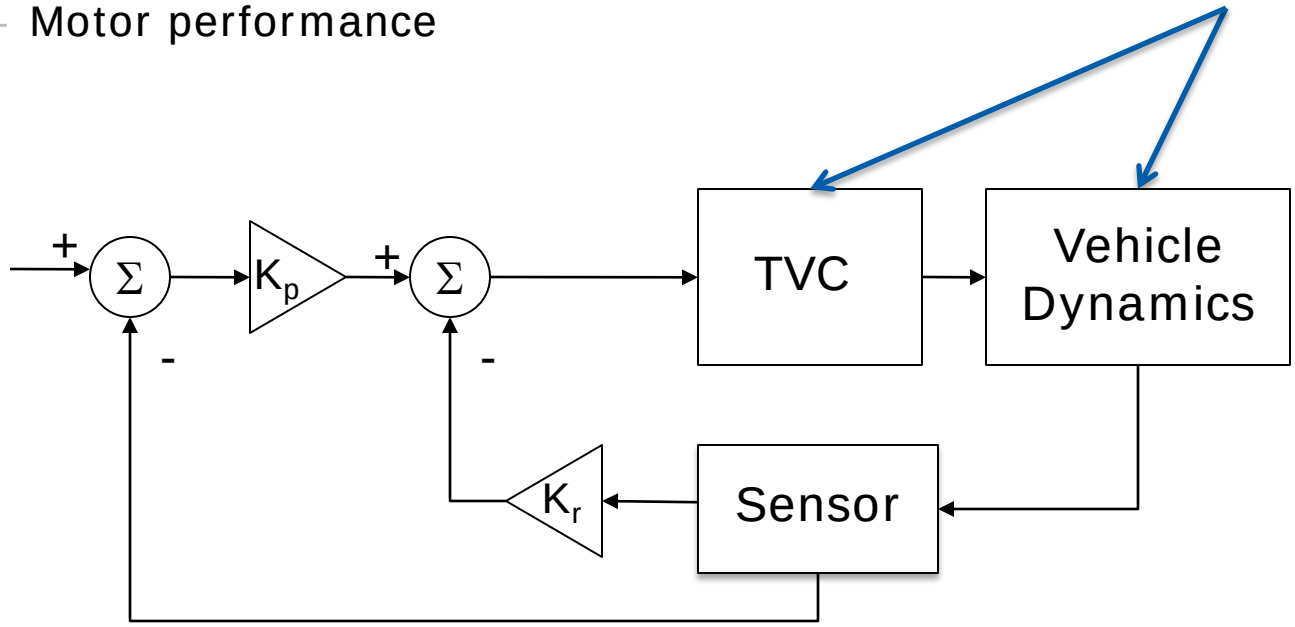
A/S Data Impacts on GN&C Analysis

- TASC RSLP Guidance, Navigation, and Control (GN&C) group performs independent GN&C analysis for IV&V
  - Requirements verification for mission risk assessment
  - Independent verification of contractor preflight predictions
- Primary GN&C Analyses
  - Linear stability analysis
    - Analysis of the autopilot design in the frequency domain used to assess the stability of the design
  - Non-linear six-degree-of-freedom (6DOF) simulation
    - Analysis of the GN&C design in the time domain used to assess launch vehicle performance with respect to requirements
    - The six degrees of freedom are the three degrees of freedom in position and the three degrees of freedom in orientation
  - Linear stability analysis and 6DOF analysis both affected by A/S data

Linear Stability Analysis of Autopilot Design

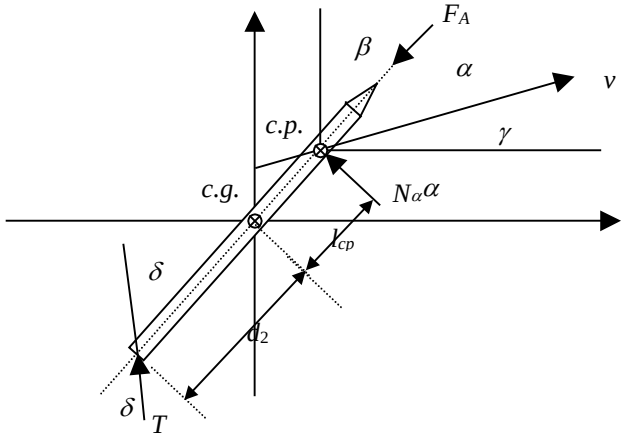
- A linear model of the launch vehicle under boost flight and a linear model of the autopilot design are created
- A/S modeling updates propagate into the propulsion and TVC models
  - Thrust Vector Control (TVC) stiffness
  - TVC slew rate
  - Motor performance

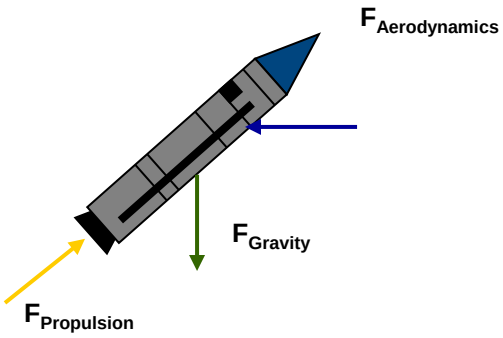
TVC linear model and motor models kept current with A/S Data



6DOF Simulation Analysis

- Analysis used to produce pre-flight predictions of launch vehicle performance
- A mathematical model of aerodynamics, propulsion, gravity, TVC, etc. are used to calculate the sum of the forces and moments acting on the vehicle
- Given a mathematical model, data representative of a specific vehicle is used
- TVC and propulsion models kept current with A/S data





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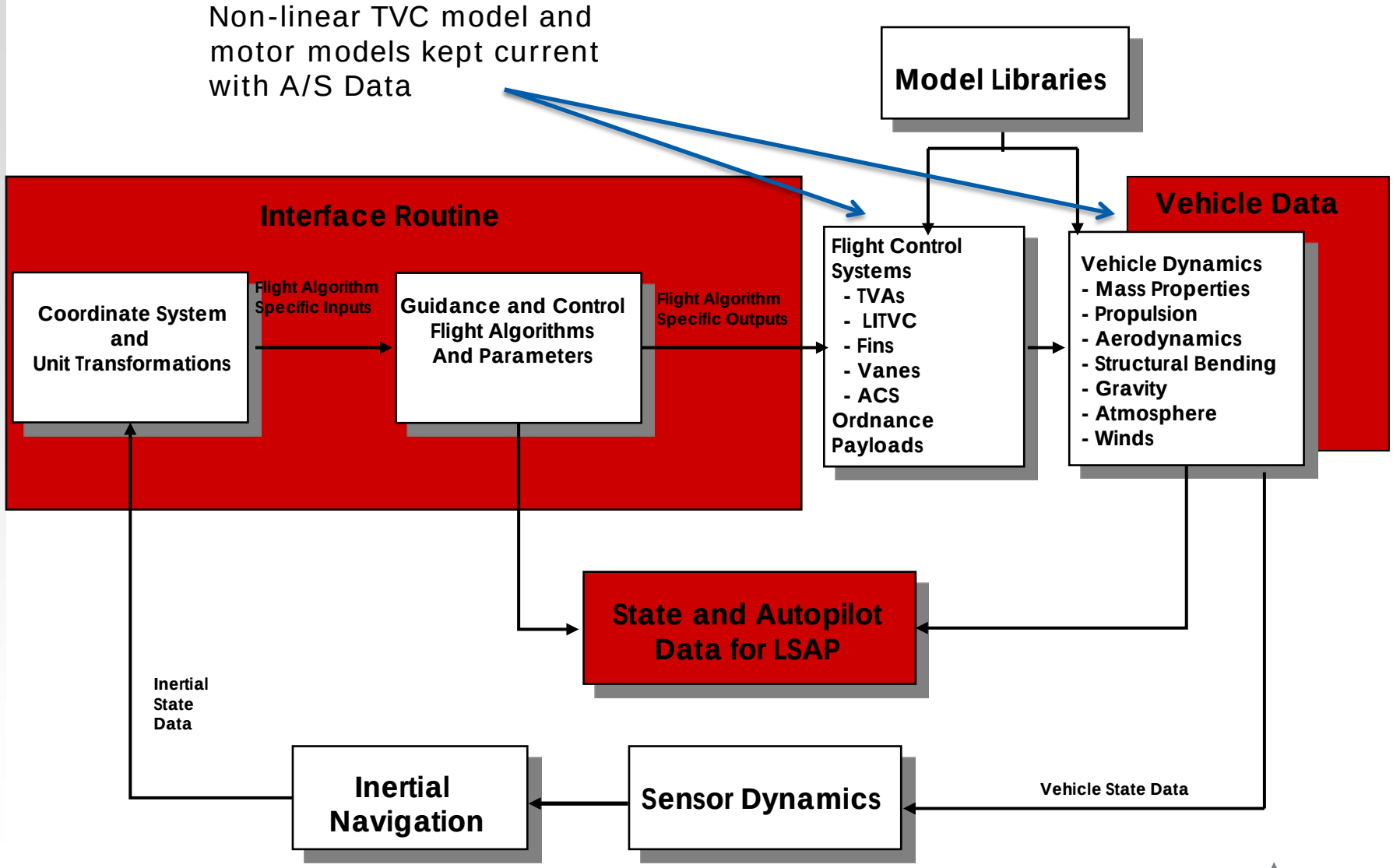

Summary / Wrap-up

- Proper surveillance of aging assets is necessary to maintain confidence in the reliability of solid rocket motors
- The RSLP A/S program provides high confidence that the Minuteman II and Peacekeeper motors continue to provide a reliable boost capability