Future Quantum-Leap Instrumentation & Sensor Technology Needs for Space Vehicles

(Note: This presentation does not represent any NASA official position. All expressed views are strictly my own.)

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Schools attended

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- *44-Year NASA JSC career in the structures-loads-dynamics technical disciplines, structures/vibration lab manager, and Space Shuttle chief engineer for the JSC Structural Engineering Division*

- *Current: Loads & structural dynamics and technical support/oversight to the integrated Space Launch System & Orion-Multipurpose Crew Vehicle and the Exploration Mission-1 system modal vibration ground tests. Active member of the Joint Loads Task Team and their analysis working group. Awaiting work on NASA's Gateway Exploration.*

- *I am no expert in sensor/instrumentation or in measured signal processing, but I have always been a customer-user. → Data from ground tests and flight tests → Analysis & math model correlations*

Current Conventional "Old Way" to Flight Test and Post-Flight Analyses

Design of Vehicle, Architecture, Operations

Math Modeling of Vehicle & Environments
Pre-Flight Vehicle Analysis Cycles (many)
Ground test programs

Fabrication/Manufacture of Vehicle and Components

Lastly: Flight Objectives & Instrumentation defined. Heavy; clunky connectors, wires, recorders. Procured and then somehow "squeezed," force-fit, drilled, glued, and invasively mounted into space vehicle

Large engineering groups performing post-flight data analyses & math model correlations slogging away <u>for months or even years</u>.

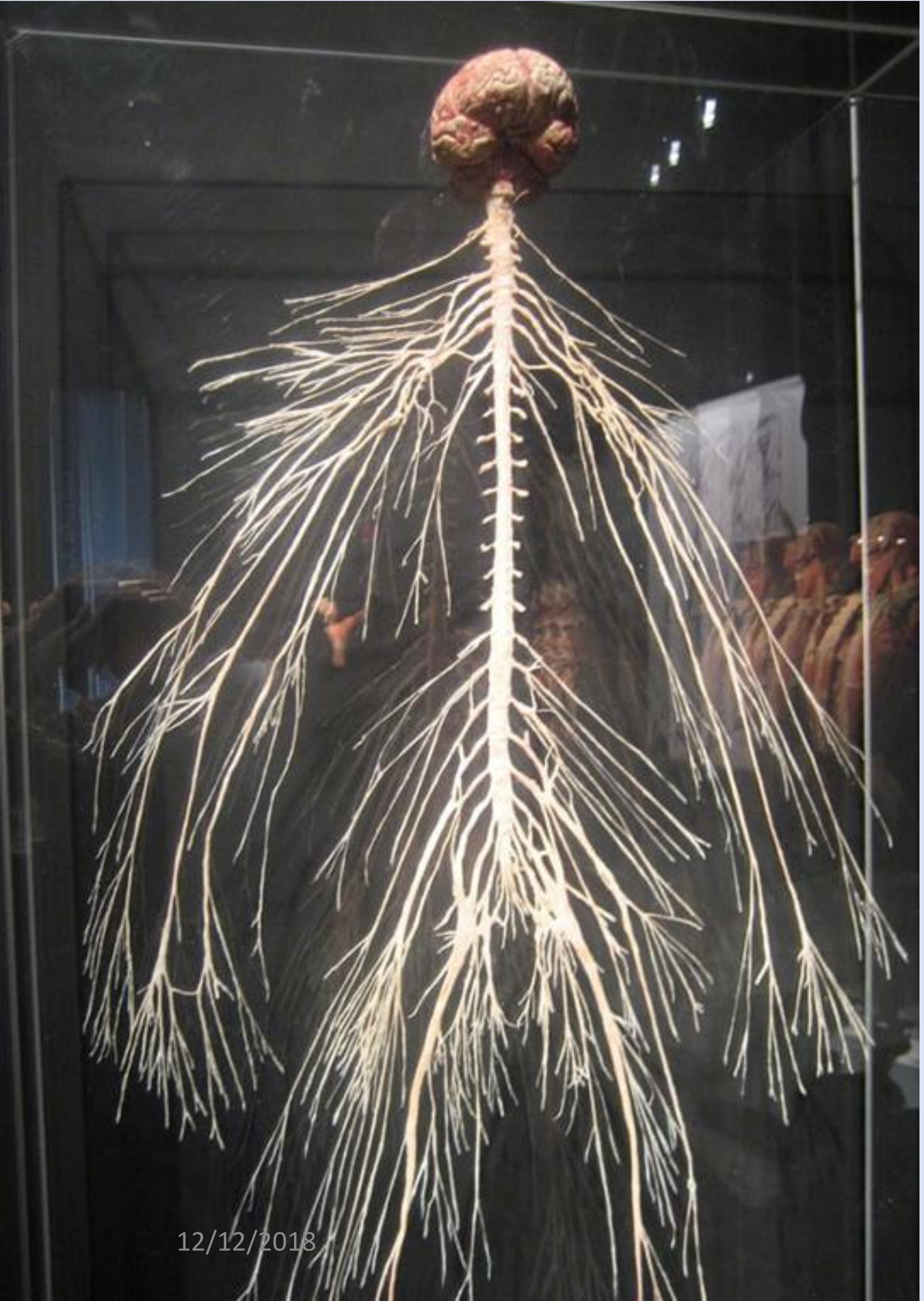
Can we not do better than this?

Post-Flight Analyses of Catastrophes and Near-Catastrophe Examples

- **Mission STS-1 maiden flight of Shuttle Orbiter Columbia**
  - Solid rocket engines' ignition overpressure too severe at lift-off.
    - Excessive flexible-body accelerations in cargo bay
    - Buckled support strut in forward fuselage, reaction control system tank
  - Surprise aerodynamics:
    - Vehicle lofted too much during early ascent due to error in vehicle base aerodynamic drag
    - Excessive aerodynamic pressure on wings; large hinge moments on elevens during trans-sonic condition (Mach ~ 1.0)
  - Orbiter/crew returned and landed safely , but could have suffered catastrophic loss

- **Catastrophic Accidents: Mission STS-51L Space Shuttle Challenger accident and Mission STS-107 Columbia: Loss of vehicles and fourteen astronauts**

- **All underwent massive, lengthy post-event data/analyses and forensics**
  - Flight & ground conditions reconstruction → Duration of months to years before returning to flight. Large dedicated engineering labor force
  - Space Shuttle Orbiter fleet continued to have some level of flight instrumentation/data recorders. However, sensor attrition and reduced capability continued throughout the program
  - Reduction in data occurred over the decades despite engineers' pushing back and Shuttle continuing to experience in-flight anomalies and scary "surprises" manifesting in flight environments and hardware. Some of these were neither fixed nor mitigated; some issues never really understood. (E.g., increased main engine acoustic levels at lift-off)



Two complex systems relying on vast amounts of data, awareness of self-status, sensing external environments, and super-fast processing for evaluation, learning, and decision-making.

The crude creature on the right must somehow catch up and approach the complexity and processing capabilities of the organism on left.


NASA Engineer Boy, you've been waiting so very long! What is your fondest wish?
"I want to eat lots of Big Flight Data, gulp them down, and spit out products real fast on the fly. Then I'll be real!"
NASA

Quantum Leap Must-Haves for Measuring and Processing Aerospace Vehicle Flight Data

- **More Heavy Lifting needed now** from marriage of blended hardware/instrumentation fabrication, flight data measurement, processing and hyper-rapid calculation into pre-defined, comprehensive, complex, and lots of engineering products

- **Material Benefits Infusion into Near-Future Space Programs**

  1. Smaller, but more efficient, smartly and quickly informed engineering work force
  2. Potential to achieve large weight-savings and thus more efficient aerospace structures. → Critically needed for future launch vehicles and for human deep space exploration vehicles.
  3. Fast turn-around between missions. Substantial reduction in analysis time between flight tests and achieving operational utilization from development to mature vehicles.
  4. Large cost and engineering labor savings in the long term

What Needs to Be Cobbled Together

- **Assumption 1**: Embedding technology is evolving at a fast pace for practical embedding sensors/instrumentation directly into structural fabrication, manufacturing, and vehicle assembly. Very light weight and wireless, if possible. Avoid and/or protect against EMI.

- **Assumption 2**: On-board vehicle host/storage large storage capability will exist for pre-flight uploading of structure Finite Element Models per flight configurations; material property cards; aerodynamic force/pressure patches; vehicle rigid-body inertia properties per flight configuration; etc. Similar to Space Shuttle pre-launch uploading of ILOADS for ascent flight control and wind shear protection.

- **Motivation 3 New Technology, Accelerated Push:** On-board dedicated computers & processors → Boosting capabilities for rapid (near real time) calculation of numerous critical products (examples follow). Perhaps on-board combination of smart systems & artificial intelligence surpassing today's state.

- **Assumption 4**: NASA and aerospace companies project & program management, *from the beginning*, will *commit* to items 1, 2, and 3 above as top priorities in launch vehicle architecture, design, stronger program and technical integration, fabrication/manufacture of structural components, more thorough & standardized ground tests, flight test requirements & objectives, Go/No-Go launch commit criteria or flight rules, and more…

General Methodology

Pre-loaded Vehicle Info: Models, materials and mass properties, geometry, material & design allowables, primary and secondary load limits, GFE load limits, flight conditions, selected analytical environments, forcing functions best estimates …

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Pre-loaded executable applications: Software with algorithms, load/strain calibration curves/tables, load combination formulae, stress formulae, …

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Flight measured data: Low-frequency accelerometers, medium- and high-freq. accels., strain, temp., external/internal pressures, acoustics, deflections, GNC state vector, aero parameters, propulsion data, fuel/oxidizer tank levels, etc.

On-board conditioning, filtering, combining, time-synchronization, processing of flight measurements.

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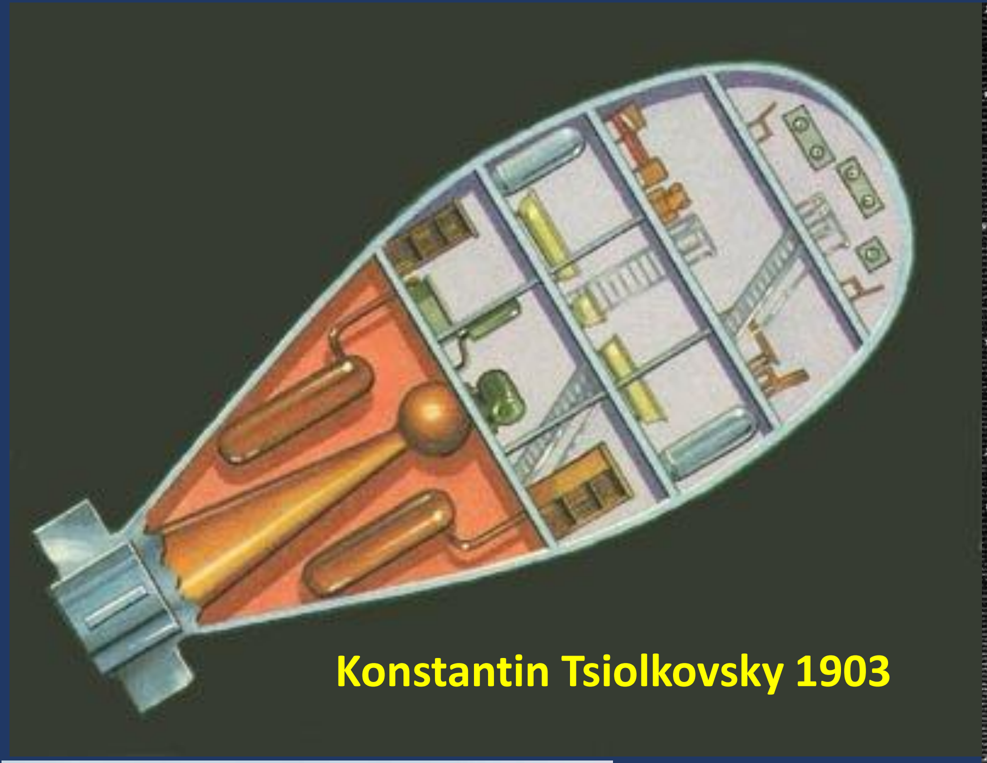
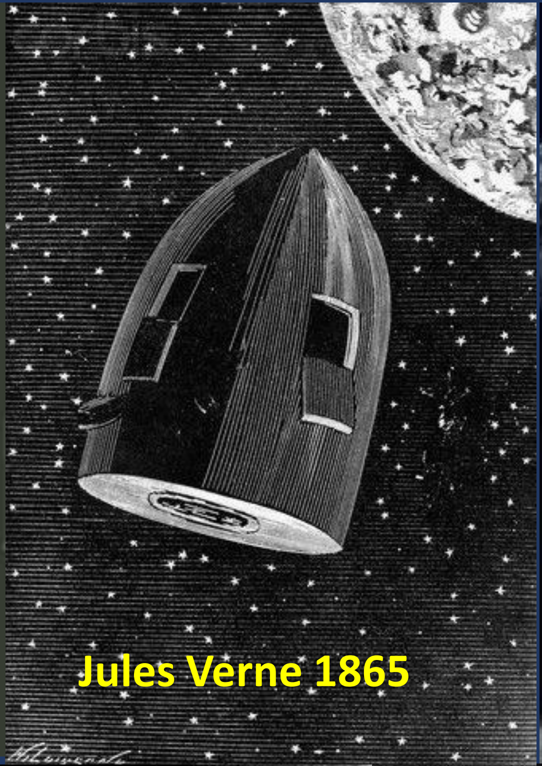
Adjustments, interpolations for sensor attrition, failures, EMI, excessive noise.

On-board calculation of numerous engineering products, evaluations, comparisons between predicted/actuals, model correlations, in-flight anomaly identification

On-board recording of products (later recovery, if possible) and/or telemetry of products to ground stations. Fast data pipe to the NASA engineers, analysts and all customers.

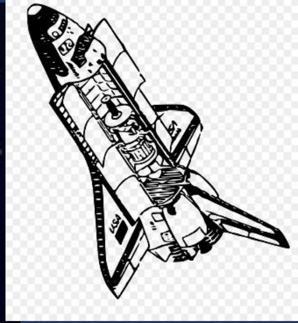


Konstantin Tsiolkovsky 1903



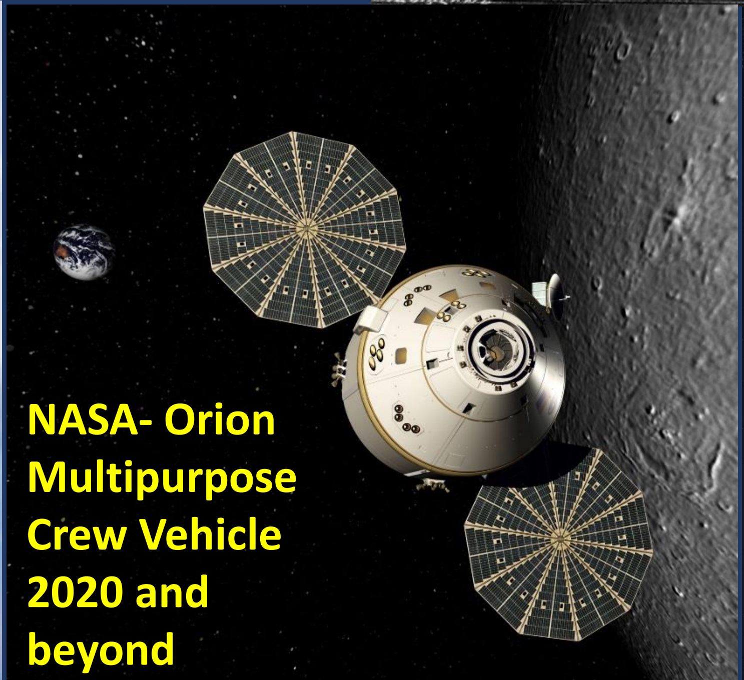
Jules Verne 1865

H.G. Wells 1901

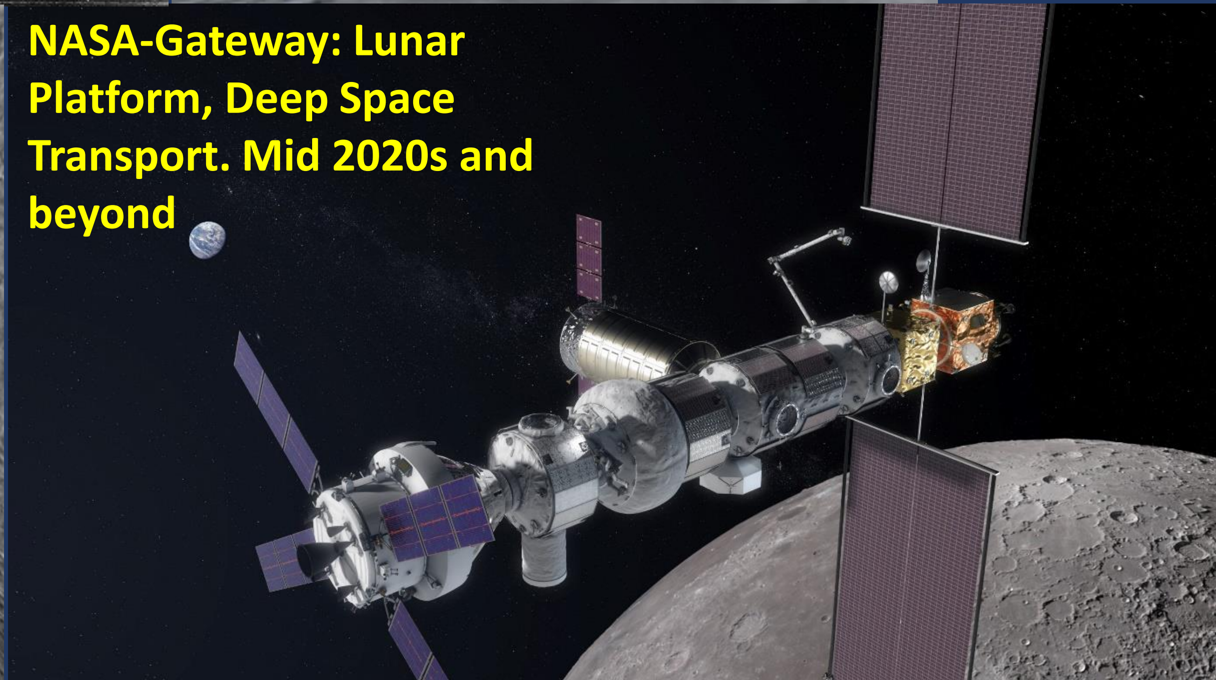


Maxime Faget - Space Shuttle fleet 1981-2011

NASA-Space Launch System 2020 and beyond



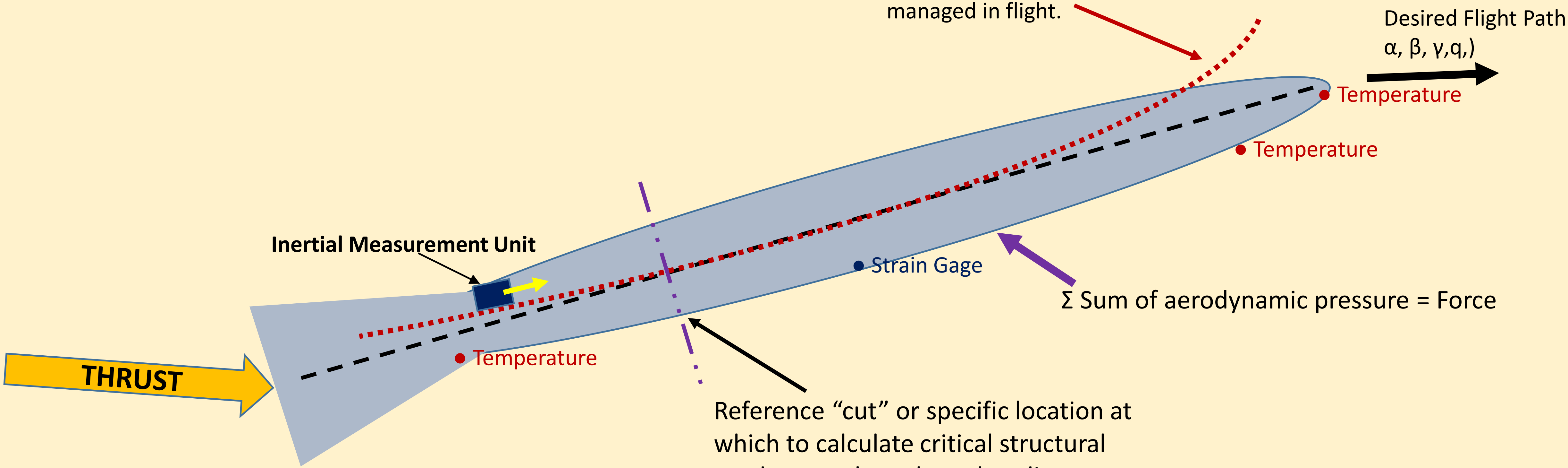
NASA- Orion Multipurpose Crew Vehicle 2020 and beyond



NASA-Gateway: Lunar Platform, Deep Space Transport. Mid 2020s and beyond

Generic Aerospace Vehicle in Flight:
The Tsiolkovsky-Verne-Wells-Oberth-VonBraun-Goddard Rocket

Flexible mode shapes of the total vehicle must not only be predictable, but managed in flight.

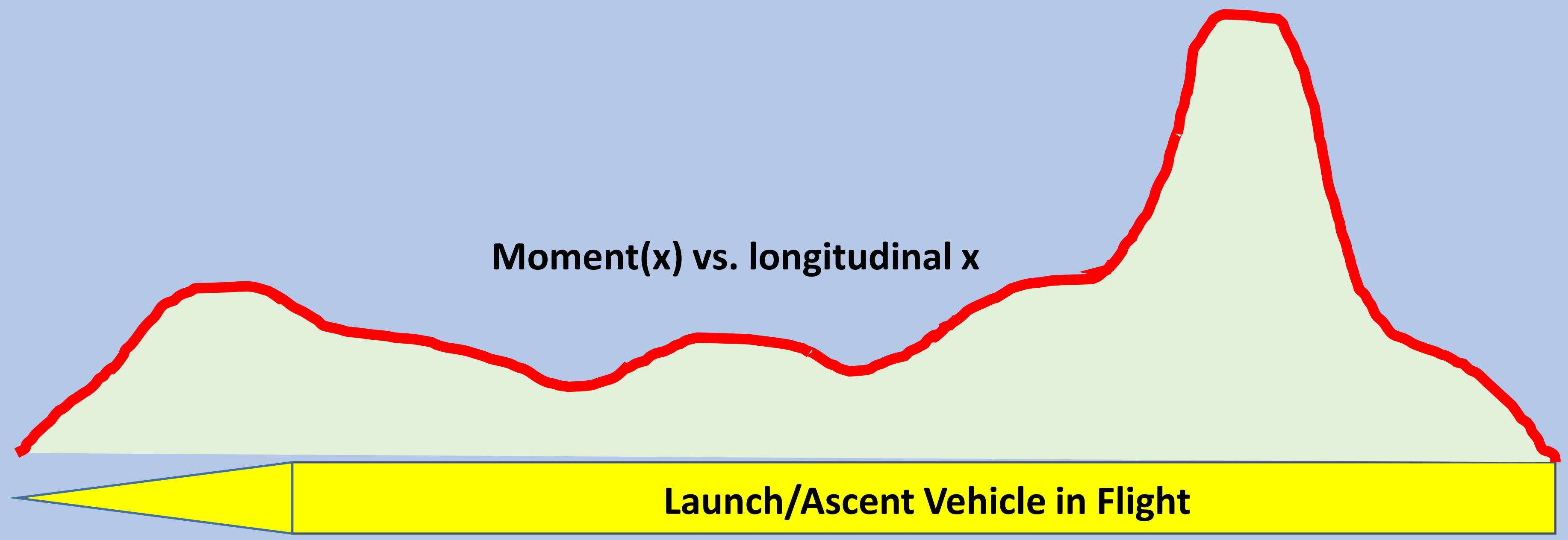


Reference “cut” or specific location at which to calculate critical structural products such as shear, bending moment, torque, axial force, internal element strain/stresses, accelerations, and relative displacements.

Examples of Processed Engineering Products

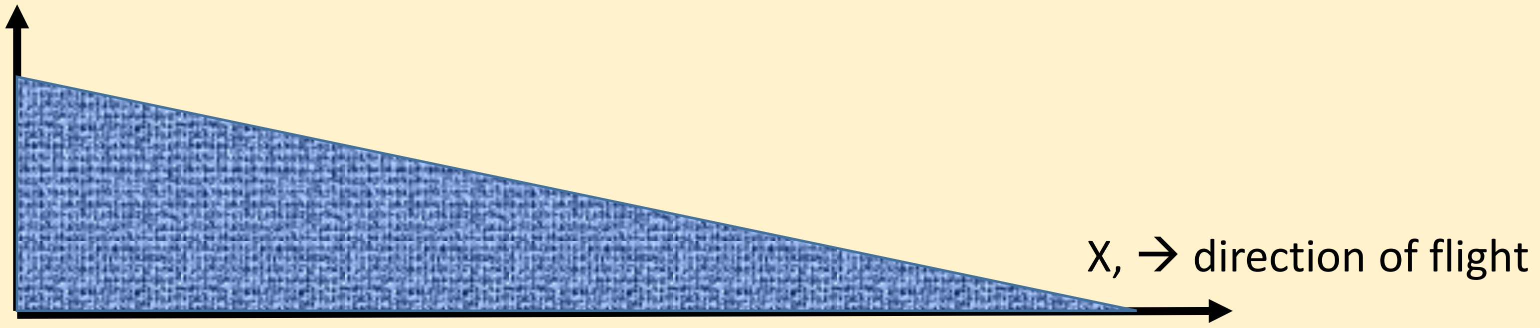
- Loads vs. Capability; Bending & Torsion Moments; Maxima/Minima Table Summaries
- Load Indicators vs. Red Lines; Section Running Loads, Static Equivalent Load, Axial Load Equivalent; Comparison to Preflight Envelopes
- Time Histories: Acceleration; Relative Velocity; Relative Displacement; Maxima/Minima
- Strain; Mechanical Stress; Thermal Stress; Principle Stress; Maxima/Minima
- Buckling Criteria Exceedance; Local Yielding
- Structural Margins from Stress
- Fourier Transforms; Frequency Peak Identification
- Frequency Response Functions / Transfer Functions
- Power or Acceleration Spectral Density (Structures-Borne Vibro-Acoustics
- Acoustics Spectral Density Operational Modal Analysis
- Local Forcing Function Identification: Ignition Overpressure, Coherence & Wave Propagation; Local Buffet, Aerodynamic Pressure Distribution, shock
- Operational Modal Analysis: Modal Frequencies; Vehicle Mode Shapes; Frequency Tracking vs Flight Condition; Damping of Structure & Tank Fluids
- Detection: Rogue wind gusts; wind shear; slosh mode excitation; external force/pressures "surprises"
- Control Structural Interaction; POGO; Aero-Elastic Vehicle Bending; Detection of "Negatively Damped" (growing) Vehicle Dynamic Response; Instability
- Detection of failed load paths and subsequent load redistribution; crack growth
- In-Flight Anomaly; Location & Time of Occurrence→ Corresponding Total Flight Condition Reconstruction
- Mechanism Deflections/Rotations + Many More…

Example: Static Equivalent Load Curve (Axial, Shear, or Moment) vs. Vehicle's Longitudinal Axis



STatic Equivalent Load, STEL = Load distribution curve on the vehicle where the inclusion of acceleration/inertia loads convert the calculation of loads, displacement, or stress is transformed to a static flight configuration with zero acceleration. (I.e., including D'Alembert inertia forces)

Axial P Load Equivalent, P_{eqv}= Thrust*(1 – m(x)/M)



Load Indicator @ critical location = $\Sigma\ (F)_i$ + C1*$ACCEL_{cm}$ + C_2*q*α + C_3*q*β
where each strut load, $F_i = C_i * \varepsilon_i$ comes from the load/stain stored calibration curve

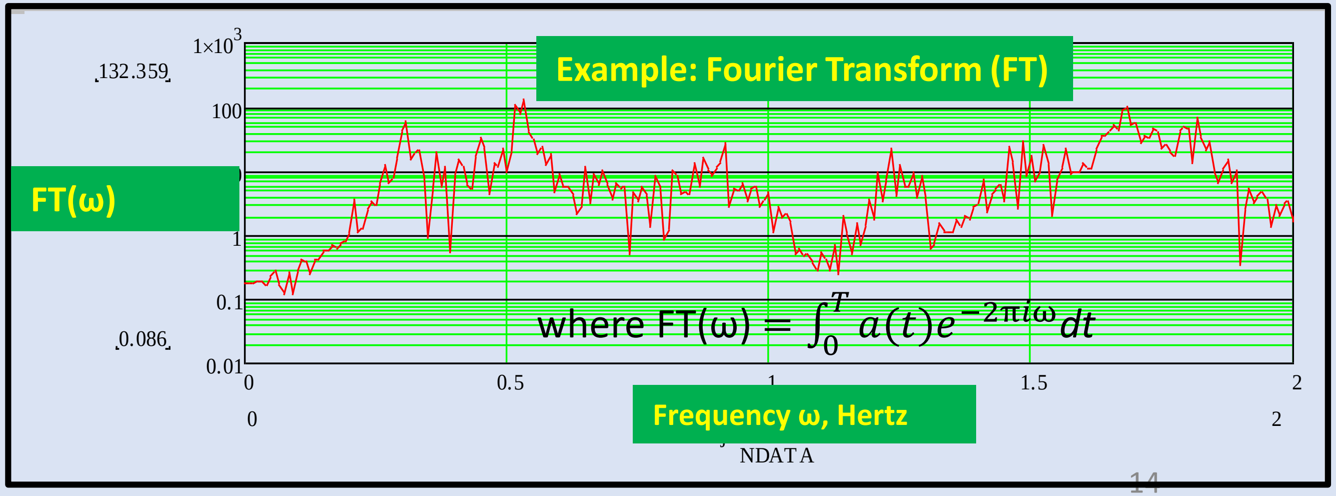
Stress, σ, from Measured Strain, ε, and Stored Material Properties

Axial element, rod, or strut σ = E*ε

Bending Stress in element, σ = M*c/I

Principle Stresses; Buckling Criteria Calculation

More complex stress formulae



Summary and Plea

- **The commitment to integrate, from the beginning of the project and vehicle design, instrumentation and engineering product generation admittedly poses a new and major challenge to large vehicle projects, especially for upcoming human-rated exploration vehicles.**

- **It is a major implementation and system integration effort. It certainly will have large initial costs.**

- **However, substantial cost savings and other benefits (weight reduction, expanded operational performance, structural efficiency, and more) will surely manifest and pay off handsomely by the time of operational routine usage.**

- **Big Data/Big Products Capability is sorely needed now. Otherwise we are stuck in the slow past. We <u>will not</u> achieve deep space exploration without it since vehicle structures will not only be unaffordable, they will be too heavy.**

- **Someone, somewhere <u>will</u> eventually develop it.**

Why not us? Why not now?