Design and Stability of an On-Orbit Attitude Control System Using Reaction Control Thrusters

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Overview

- NASA is providing preliminary design and requirements for the Space Launch System Exploration Upper Stage (EUS).
- The EUS will provide upper stage capability for vehicle ascent as well as on-orbit control capability.
- Requirements include performance of on-orbit burn to provide Orion vehicle with escape velocity.
- On-orbit attitude control is accommodated by a on-off Reaction Control System (RCS).
- Paper provides overview of approaches for design and stability of an attitude control system using a RCS.
  - Draws heavily from research and development in support of Space Shuttle and Space Station programs. Includes pitfalls and lesson's learned from flight experience.

Paper Summary

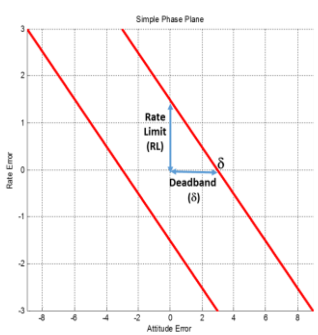
- Vehicle Attitude Dynamics and Phase Plane Control
- Phase Plane Stability and Filter Design
- Jet Selection
- Maneuver/Steering Algorithms
- Thruster Hardware Specifications

Vehicle Attitude Dynamics and Phase Plane Control

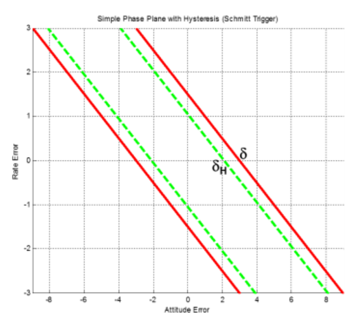
- **Attitude Dynamics are summarized:**

$$J_1\dot{\omega}_1 = (J_2 - J_3)\omega_2\omega_3 + T_{1_{ext}} + u_1$$
$$J_2\dot{\omega}_2 = (J_3 - J_1)\omega_1\omega_3 + T_{2_{ext}} + u_2$$
$$J_3\dot{\omega}_3 = (J_1 - J_2)\omega_1\omega_2 + T_{3_{ext}} + u_3$$
$$\eta = \cos\left(\frac{\varphi}{2}\right) \qquad \dot{\eta} = -\frac{1}{2}\varepsilon^T\hat{\omega}$$
$$\hat{\varepsilon} = \hat{a}\sin\left(\frac{\varphi}{2}\right) \qquad \dot{\hat{\varepsilon}} = \frac{1}{2}\left(\hat{\varepsilon}^{\times} + \eta I\right)\hat{\omega}$$
$$\Lambda_{IB} = \begin{bmatrix}\eta & \hat{\varepsilon}\end{bmatrix}$$

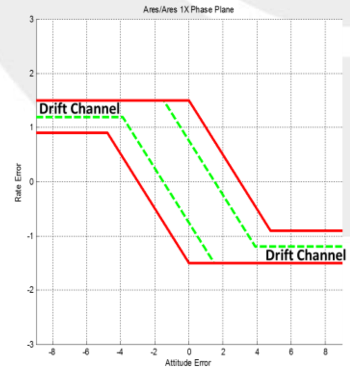
- **Phase Plane Design Examples are Provided:**



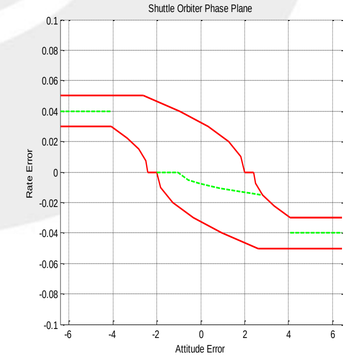
Simple Switch Lines



Hysteresis Added



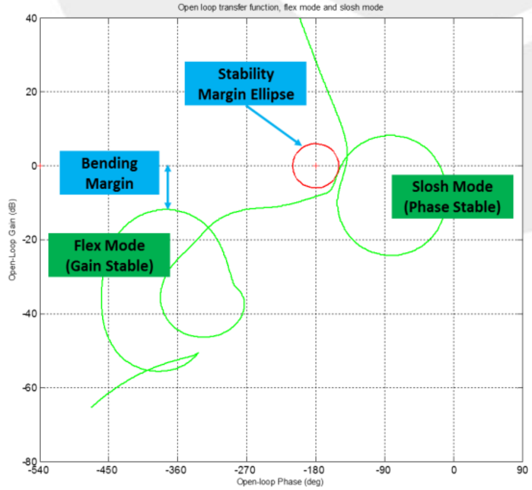
Ares I-X Design



Shuttle Design

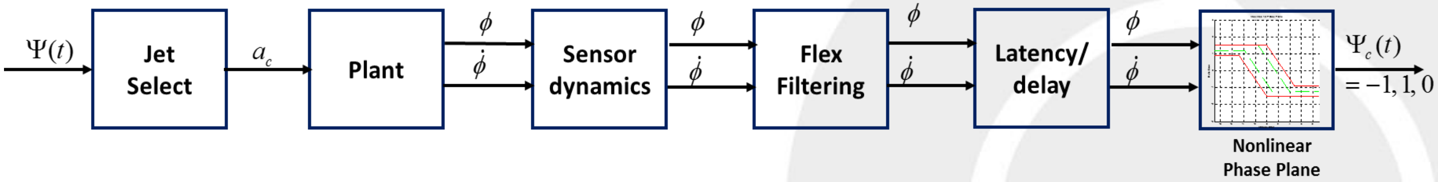
Phase Plane Stability and Filter Design

- Phase Plane control designs are nonlinear, hence traditional linear design approaches are generally not available.
- Paper presents RCS filter design and phase plane stability approaches based on research performed on the Space Shuttle and Space Station programs
  - Stability margin design goals are provided:

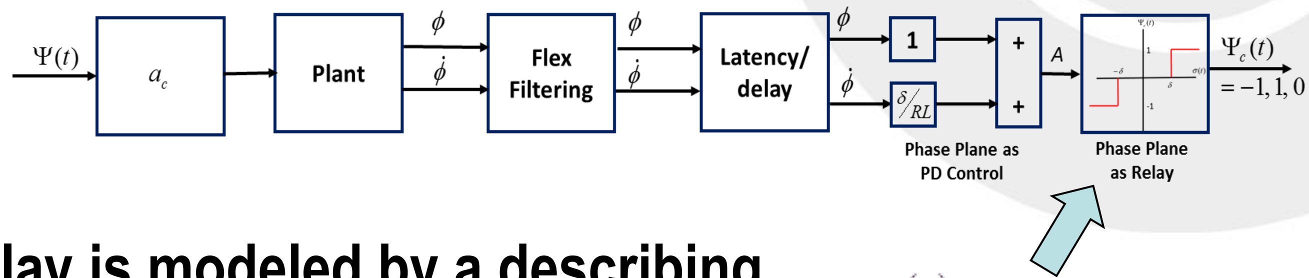


Phase Plane Stability (continued)

- Paper describes approaches to derive a linear representation of the nonlinear system, concentrating on describing functions.



- Phase plane is converted into an equivalent PD controller with a relay:



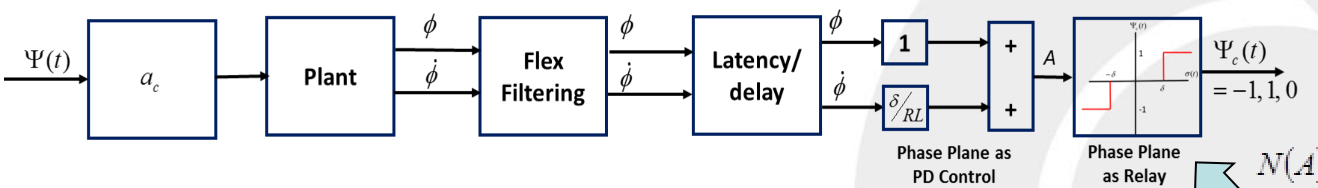
- Relay is modeled by a describing function.

$$N(A) = 0 \qquad A < \delta$$

$$N(A) = \frac{4}{\pi A}\sqrt{1 - \left(\frac{\delta}{A}\right)^2} \qquad A > \delta$$

Phase Plane Stability and Filter Design (continued)

- **Describing function relay representation is still a nonlinear system as describing function gain is dependent on input amplitude (A):**



$$N(A) = 0 \qquad A < \delta$$

$$N(A) = \frac{4}{\pi A}\sqrt{1 - \left(\frac{\delta}{A}\right)^2} \qquad A > \delta$$

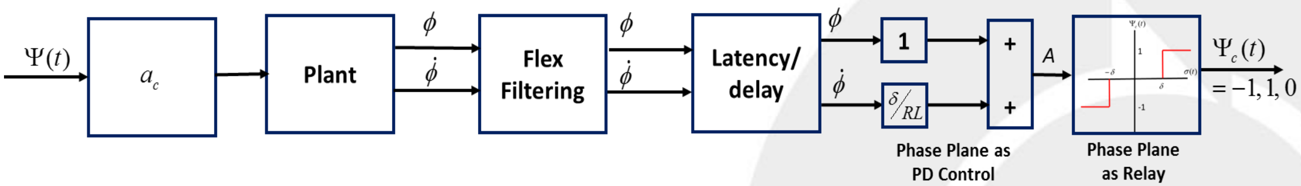
- **Linearize system by deriving value of A which maximizes the describing function (A*):**

$$A^* = \sqrt{2}\delta \quad \rightarrow \quad N(A^*) = \frac{2}{\pi\delta}$$

- **Maximizing the describing function gain represents peak RCS control response to state error, which maximizes flex response to RCS firings (conservative approach).**

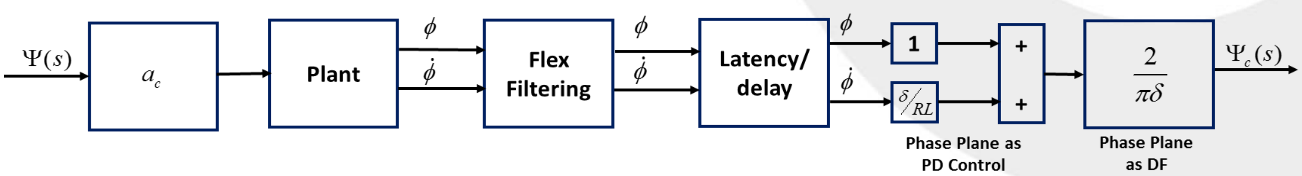
Phase Plane Stability (continued)

- **Given a System:**



- **Substitute the relay with a peak gain representation derived from the describing function:**

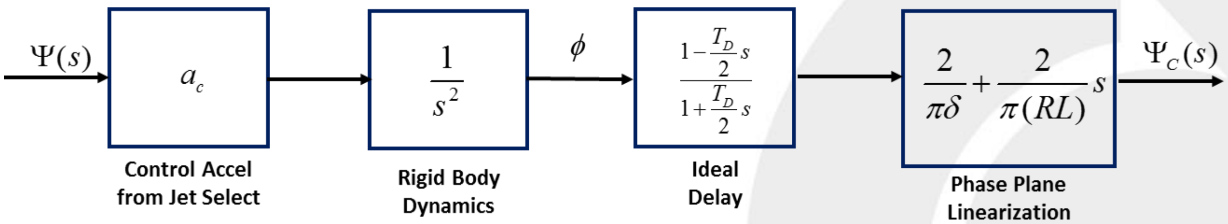
$$A^* = \sqrt{2}\delta \qquad \rightarrow \qquad N(A^*) = \frac{2}{\pi\delta}$$



- **The resulting derivation is a linear representation of phase control system.**

Phase Plane Stability (continued)

- **Example. Model rigid body control and ideal latency:**



- **The phase plane controller is a PD representation with the gains proportional to the phase plane deadzone (attitude and rate) limits.**

- **The closed loop transfer function is derived:**

$$\frac{\Psi_c(s)}{\Psi_c(s)} = \frac{\dfrac{2a_c}{\pi}\left[-\dfrac{T_D}{2(RL)}s^2 + \left(\dfrac{1}{RL} - \dfrac{T_D}{2\delta}\right)s - \dfrac{1}{\delta}\right]}{\dfrac{T_D}{2}s^3 + \left(1 - \dfrac{a_c T_D}{\pi(RL)}\right)s^2 + \dfrac{2a_c}{\pi}\left(\dfrac{1}{RL} - \dfrac{T_D}{2\delta}\right)s + \dfrac{2a_c}{\pi\delta}}$$

- **And the necessary Condition for stability derived:**

$$\frac{1}{RL} - \frac{T_D}{\delta} - \frac{a_c T_D}{\pi(RL)^2} + \frac{a_c T_D^2}{2\pi(RL)\delta} > 0$$

Phase Plane Stability (continued)

- **Given the stability condition:**

$$\frac{1}{RL} - \frac{T_D}{\delta} - \frac{a_c T_D}{\pi (RL)^2} + \frac{a_c T_D^2}{2\pi (RL)\delta} > 0$$

- **Stability thresholds can be derived:**

$$\delta > \frac{T_D - \frac{a_c T_D^2}{2\pi (RL)}}{\frac{1}{RL} - \frac{a_c T_D}{\pi (RL)^2}}$$

$$T_D < \frac{a_c \delta - \left(a_c^{\,2} \delta^2 + \pi^2 (RL)^4\right)^{1/2} + \pi (RL)^2}{a_c (RL)}$$

Smallest Deadband

Allowable Latency

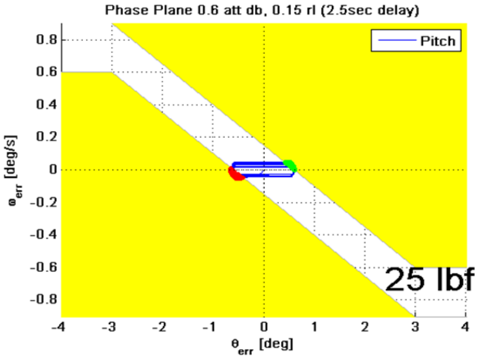
Phase Plane Stability (continued)

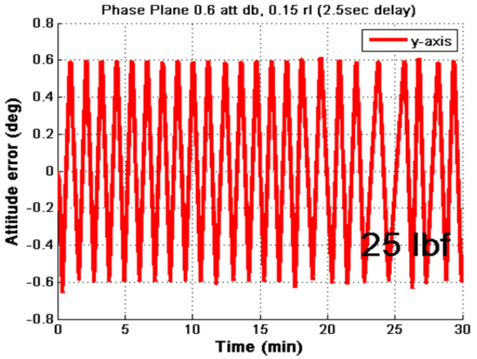
- **Paper provides an example of how the stability condition maps to the RCS time domain simulation.**

$$T_D < \frac{a_c\delta - \left(a_c^{\,2}\delta^2 + \pi^2 (RL)^4\right)^{1/2} + \pi (RL)^2}{a_c (RL)}$$

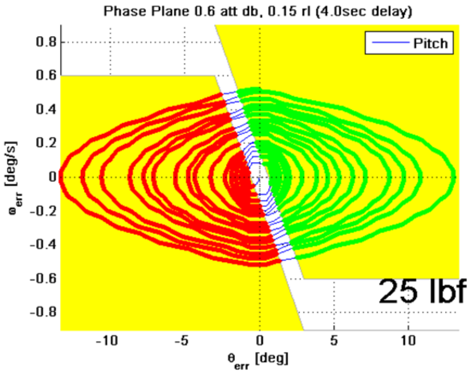
Allowable Latency

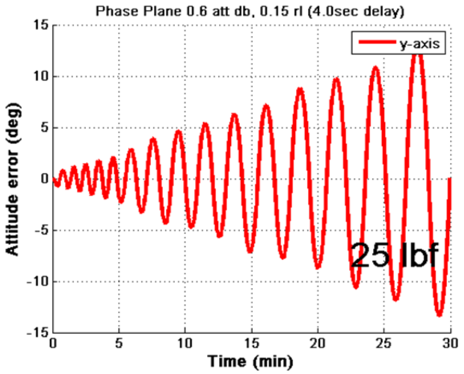
- **Stable RCS Control:**





- **Unstable RCS Control:**



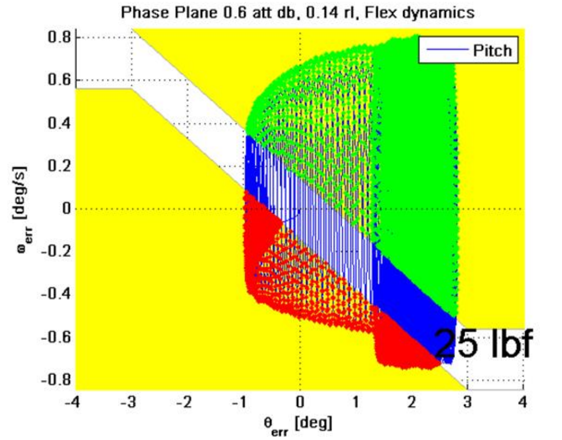


Key RCS Filter Design Principles

- **Paper provides key filter Design Principles for RCS:**
  - Key Filter Design 1: Rigid body Stability
  - Key Filter Design 2: Flex Gain Margins
  - Key Filter Design Principal 3: Minimizing Filter Induced Lag
  - Key Filter Design Principal 4: Feed Forward during Thruster Firings

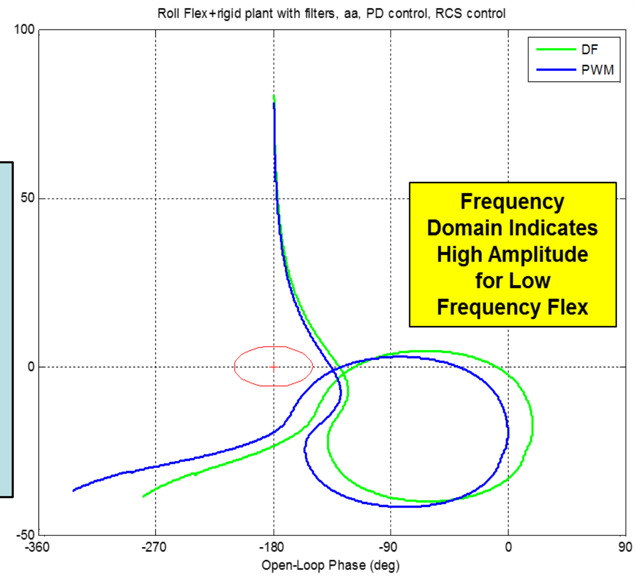
Key Filter Design 2: Flex Gain Margins

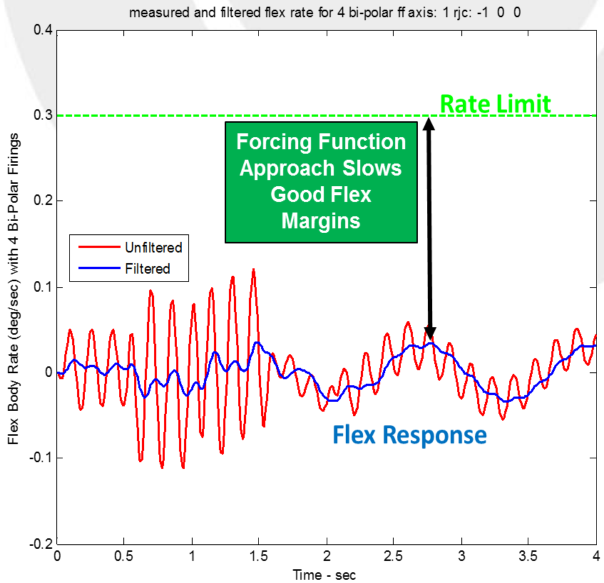
- **Flex body dynamics can drive an RCS unstable.**



Phase Plane Flex Instability

Phase Plane Stability Margins Using Linearized System

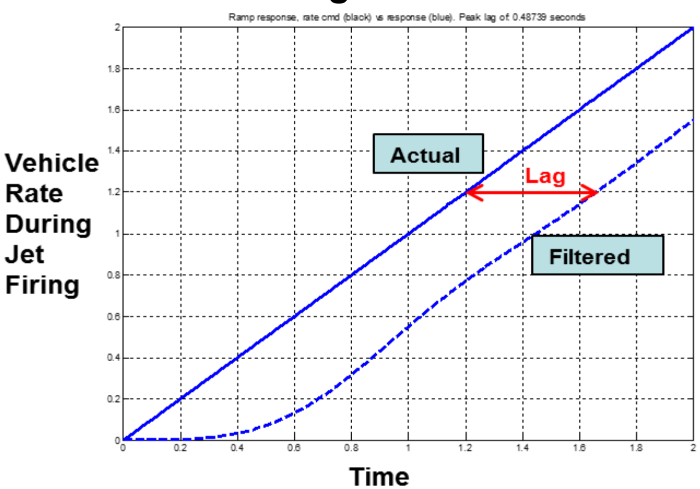


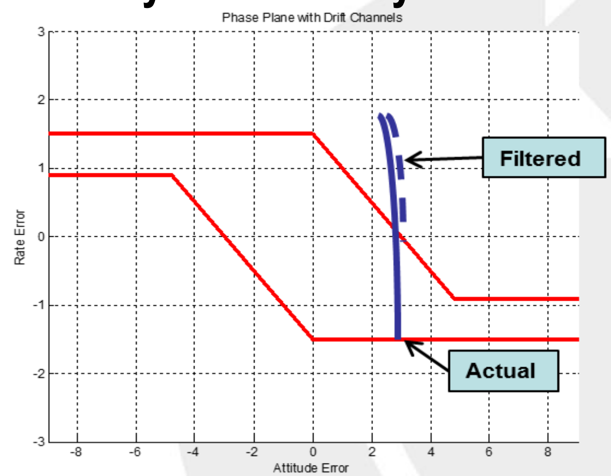


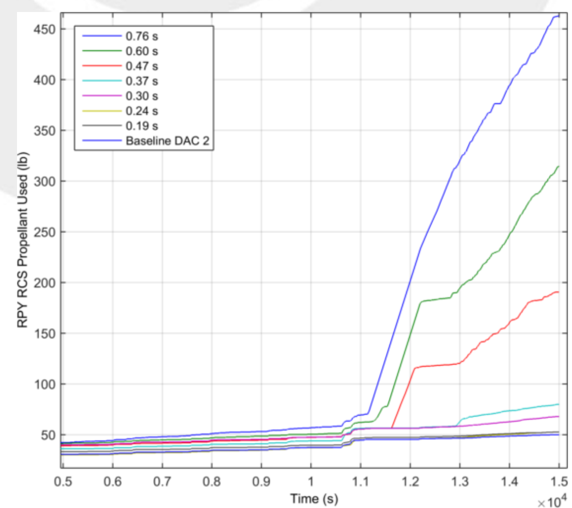
Phase Plane Stability Margins Shuttle Forcing Function Approach

Key Filter Design Principal 3: Minimizing Filter Induced Lag

- **Filter induced lag can result in a RCS limit cycle instability.**

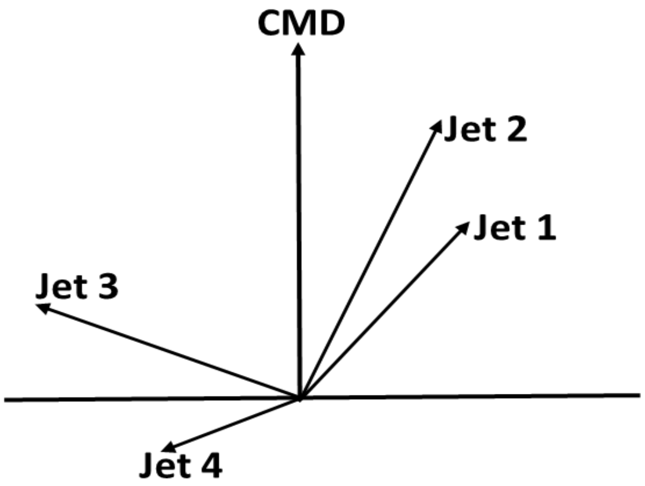






RCS Jet Selection

- **Paper Addresses multiple RCS jet selection approaches:**
  - **Table look-up.**
  - **Algorithms that accommodate mass property changes.**
  - **Fuel Optimal Jet Select.**
  - **Command preshaping to avoid structural excitation.**



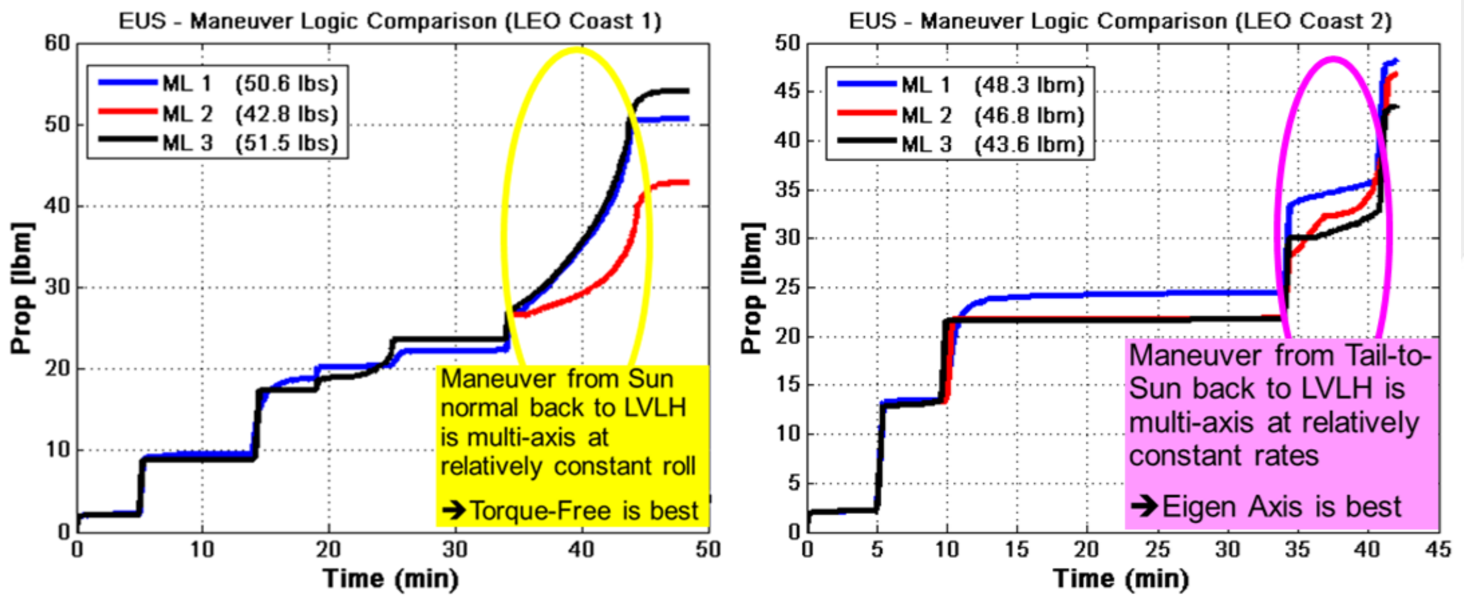
Two Space Shuttle Jet Select Algorithms

Dot Product: Would select jets 1 and 2

Minimum Angle: Would select jets 2 and 4

RCS Maneuvering/Steering Algorithms

- **Paper Addresses multiple RCS maneuvering/steering approaches:**
  - **Eigen Axis Maneuvers.**
  - **Torque-Free Maneuvers (Russian MIR).**
  - **Steering Formulation.**
  - **Fuel Optimal (Space Station “Zero Prop Maneuver”).**



Thruster Hardware Specifications

- **Discusses Shuttle RCS hardware design/control criteria:**
  - ***Control authority must exceed all known disturbances by a factor of two.***

$$\hat{T}_C > 2 * \left[\max\left(-\hat{\omega} \, x \, \hat{J}\hat{\omega} \right) + \max\left(\hat{T}_{ext} \right) \right]$$

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