National Aeronautics and Space Administration

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SPACE LAUNCH SYSTEM

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Sub-Minimum Impulse Attitude Control of Spacecraft

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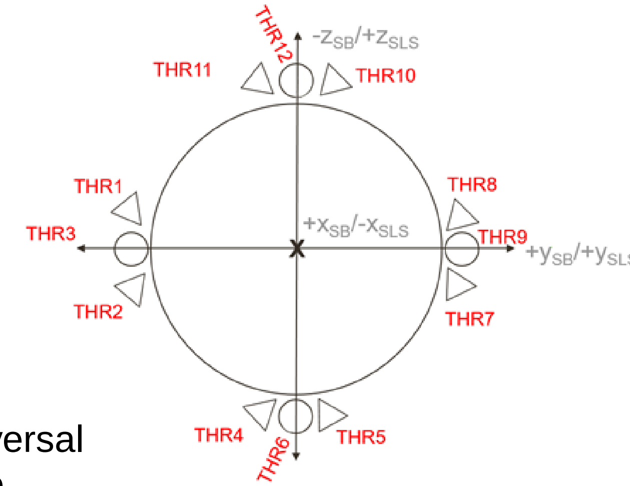
Agenda

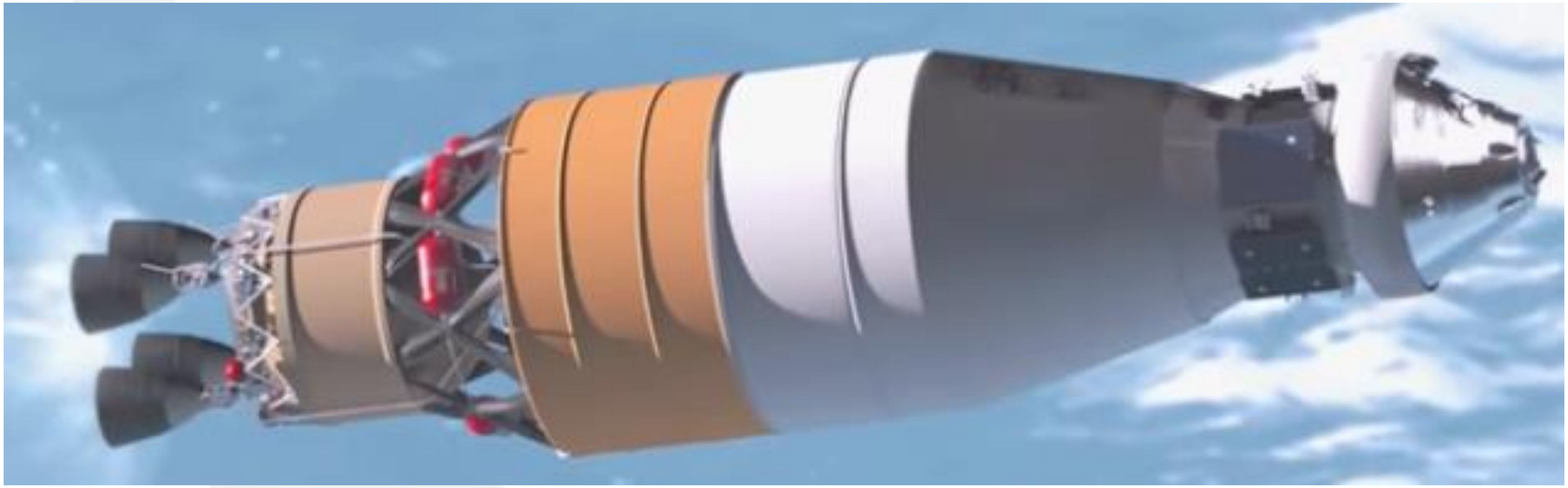
- **SLS EUS Configuration**
- **Baseline Control Algorithm and Limitations**
- **Control Algorithm Solutions**
  - Feed Forward State Estimator
  - Minimum Impulse
  - Sub-Minimum Impulse
- **Monte Carlo Results**
- **Conclusions**

Exploration Upper Stage (EUS) Vehicle Configuration

- **Rendezvous, Proximity Operations, and Docking (RPOD) occurs after the Orion Multi-Purpose Crew Vehicle (MPCV) separation and jettison of the Universal Stage Adapter in Artemis IV (previously Exploration Mission II).**
- **Eight attitude Reaction Control System (RCS) thrusters, already chosen by the prime contractor based on NASA specifications, located behind the center of mass of the spacecraft, provide roll, pitch, and yaw control/ maneuvers.**

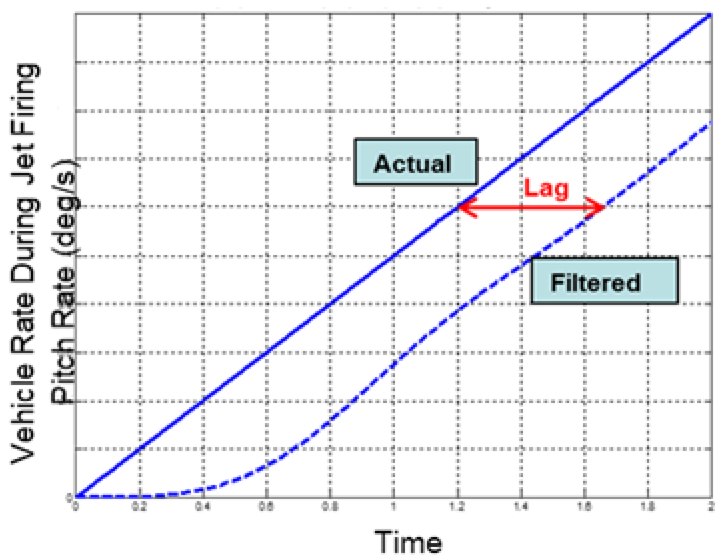


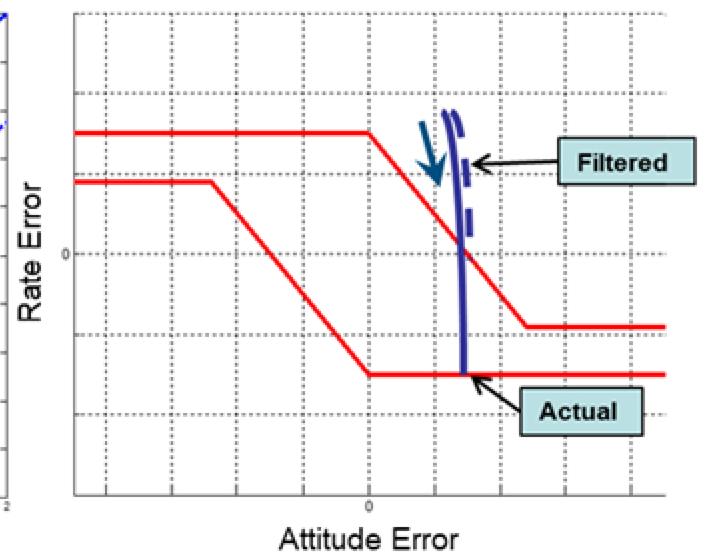
Space Launch System (SLS) Exploration Upper Stage (EUS) With Universal Stage Adaptor, Spacecraft Adapter, Service Module, and Orion Capsule.



Baseline Algorithms and Limitations

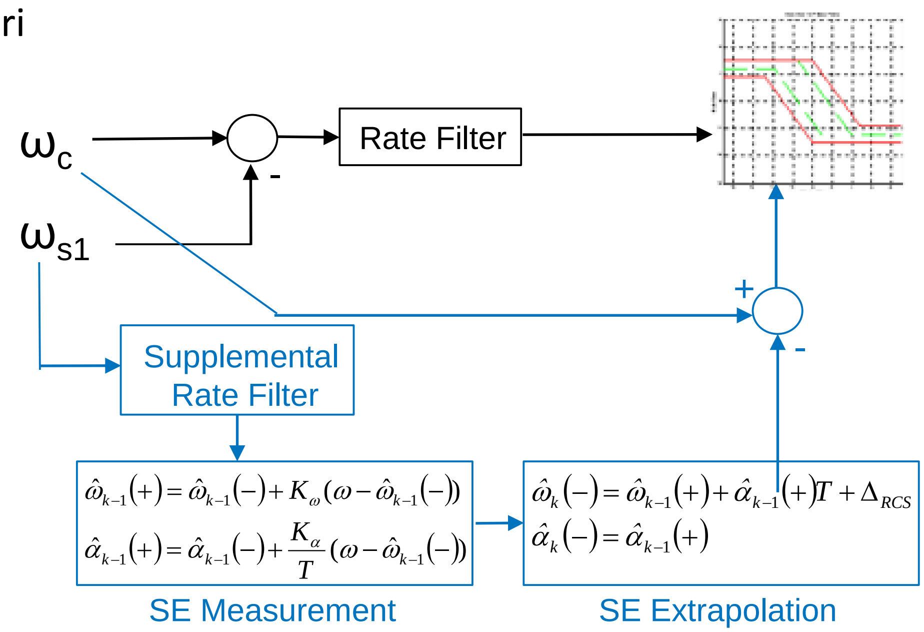
- **During docking, the Orion is the active vehicle, while the EUS is the passive vehicle performing an attitude hold.**
- **EUS and Orion were assigned significantly reduced portions of the International Docking System Standard[2] (IDSS) requirements during docking. IDSS calls for < 0.2 deg/s in Roll and < 0.2 deg/s for the vector sum of pitch/yaw relative between vehicles.**
- **Baseline phase plane simulation results exceeded initial allocations by up to 700% in Monte Carlo runs!**
- **For this algorithm, the min rate achievable is limited by the max of these constraints:**
  - Thruster minimum impulse or firing duration, and
  - Control loop latency (Sensors, Bus, Flight Control System (FCS) / Flight Software (FSW), Hardware Controllers, Flex Filters).





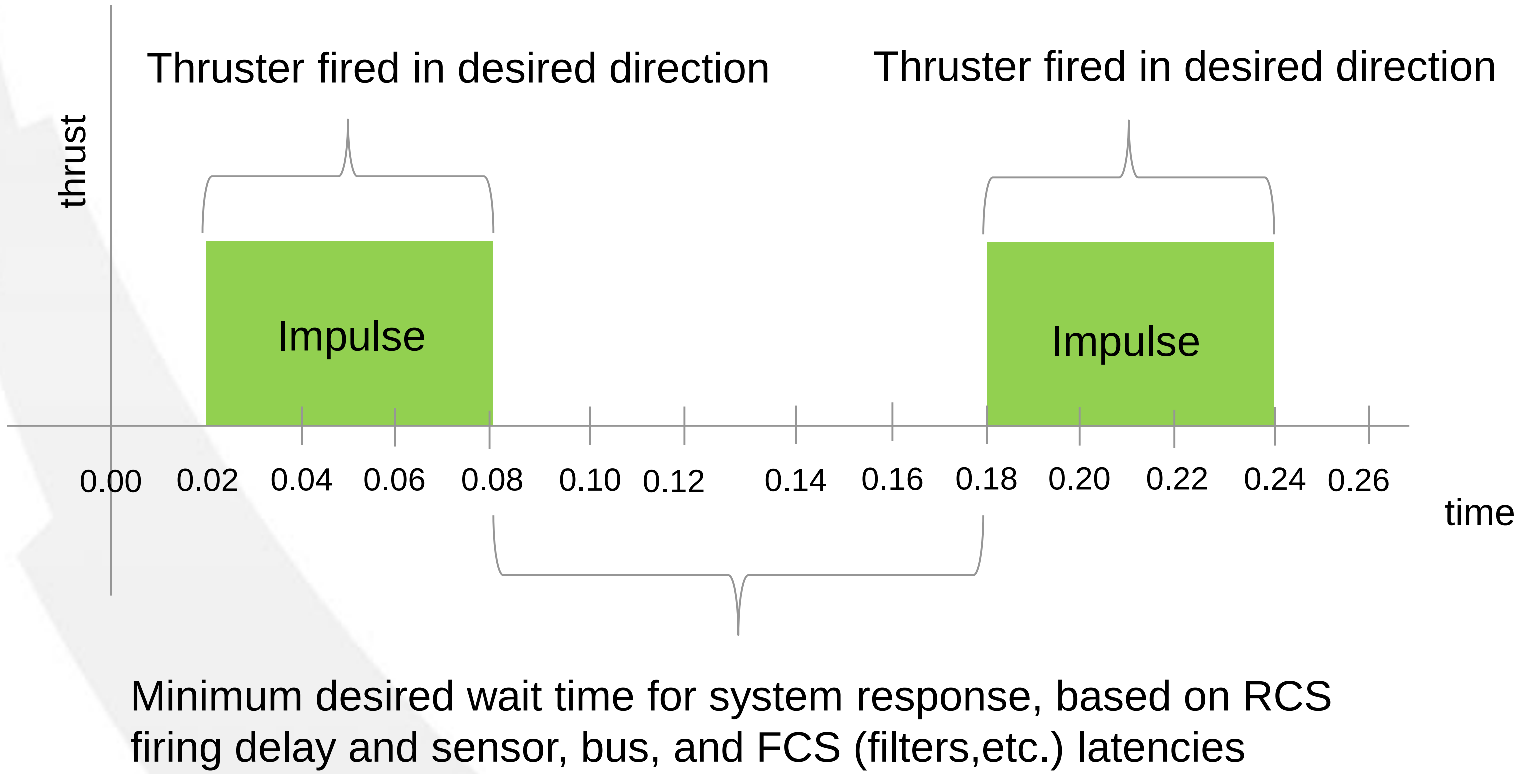
Alternate Control Modes Developed for Docking / Attitude Hold

- **Feed Forward State Estimator (FFSE)**
  - FFSE is a second order Luenberger Observer.
  - Typically not all vehicle states are directly measured, hence an "observer" is used to *estimate* unmeasured states.
    - For example, Apollo[3] and Shuttle[4] on-orbit RCS control had attitude measurement input, so the software estimated rotational rate and rotational acceleration.
    - The approach here was derived from Apollo and Shuttle.
    - Filter gains are based on stability and performance.
  - The basic premise is that feed forward of the expected thruster firing torque to minimize latency while using the state estimator to remove error, attenuate flex (with a supplemental filter), and better estimate rate.
  - The current implementation uses a priori data thrust and mass properties to compute a feed forward signal (estimated rate of change from a firing). Future investigations could include higher fidelity thrust profile and potential use of RCS tank pressure measurements.
  - Another application is RCS thruster Failure Detection Isolation and Recovery.



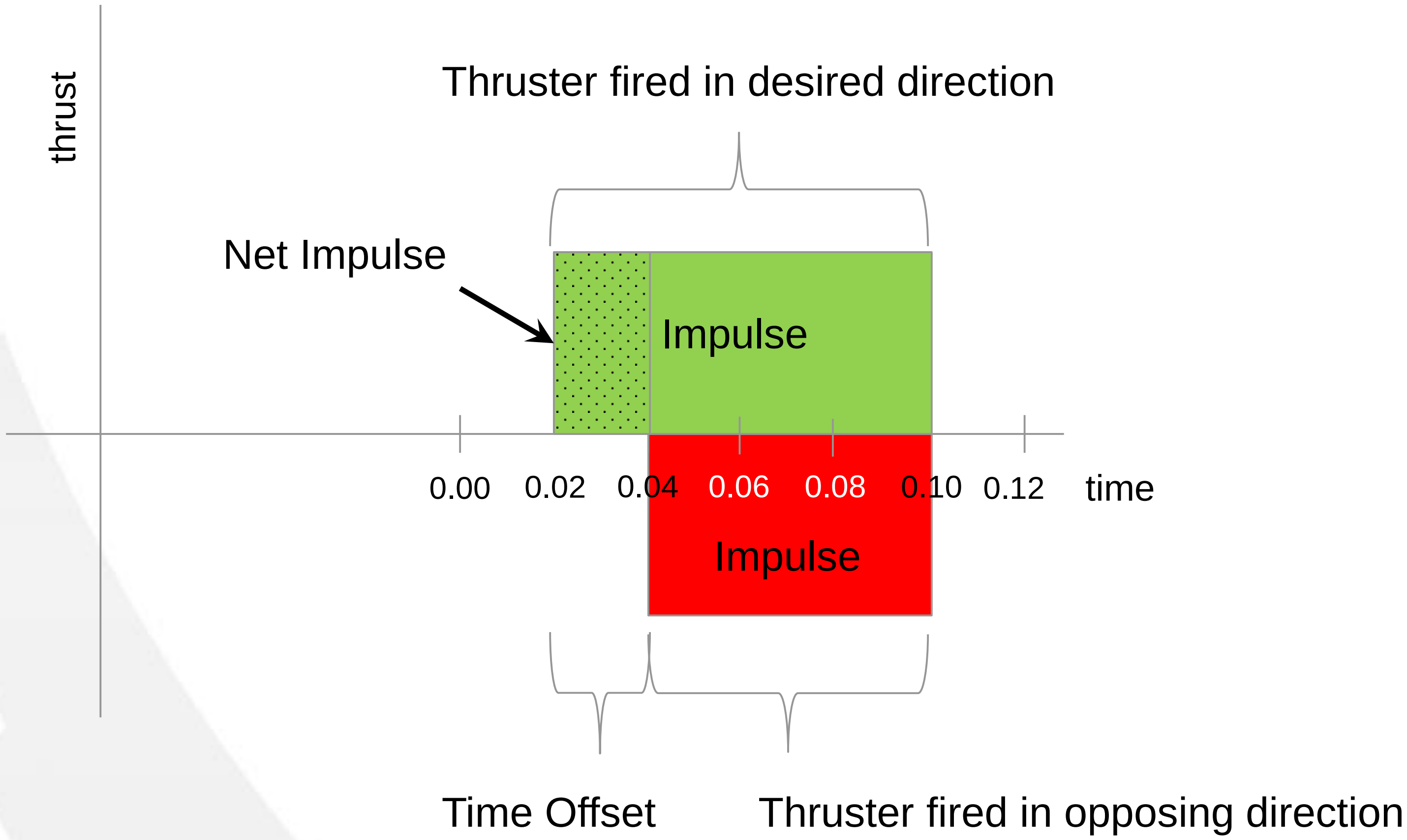
Alternate Control Modes Developed for Docking / Attitude Hold

- **Minimum Impulse Mode**
  - Issues thruster firing commands at fixed duration (min firing time) and then waits (time based on system latencies:) before firing again to allow the filtered rate measurement to converge on the true vehicle rate.
  - Can only shorten the pulses to the capability of the thrusters. As pulses get shorter, uncertainty increases in the amount of thrust produced due to incomplete propellant oxidation.
  - Currently has logic in place to exit out of this mode when large phase plane excursions are observed.



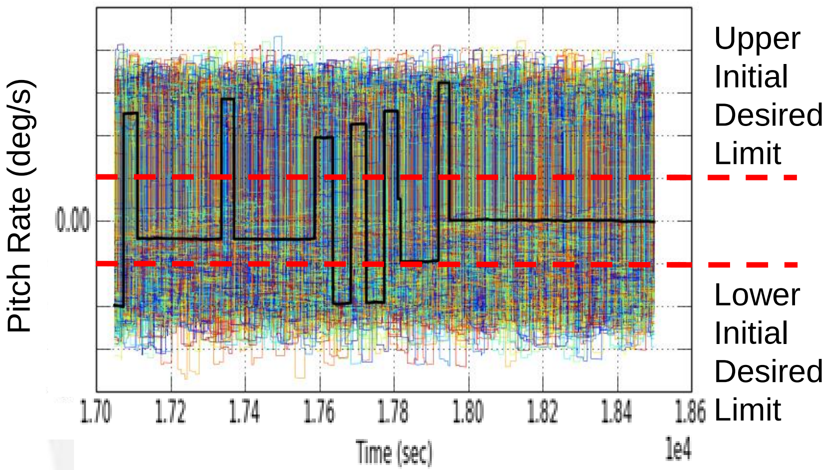
Alternate Control Modes Developed for Docking / Attitude Hold

- **Sub Minimum Impulse Mode**
  - Is a potential enhancement to Minimum Impulse Mode where opposing thrusters are fired with a time offset to reduce the net torque on the vehicle below the minimum impulse level.



Monte Carlo* Results for 4 of the Control Options Considered – Pitch Rate

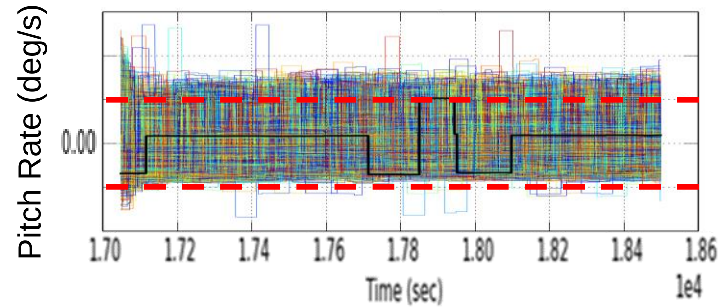
Standard Phase Plane – Original Baseline



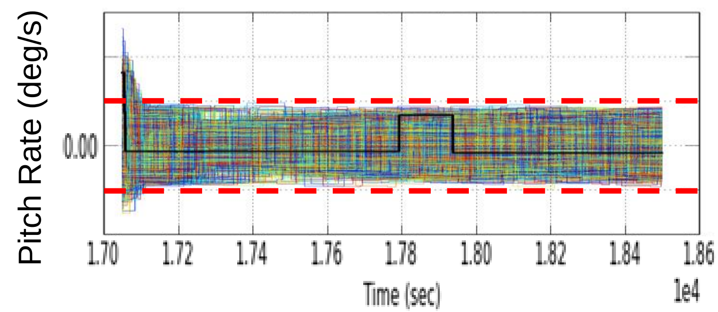
* 2000 runs were executed per case in the Marshall Aerospace Vehicle Representation in C (MAVERIC) modeling and simulation tool.

**Results were very similar for roll, pitch, and yaw for a combined Feed Forward State Estimator with Minimum Impulse with 0ms wait time. The 0 ms wait time allows for quicker response in the presence of disturbances.

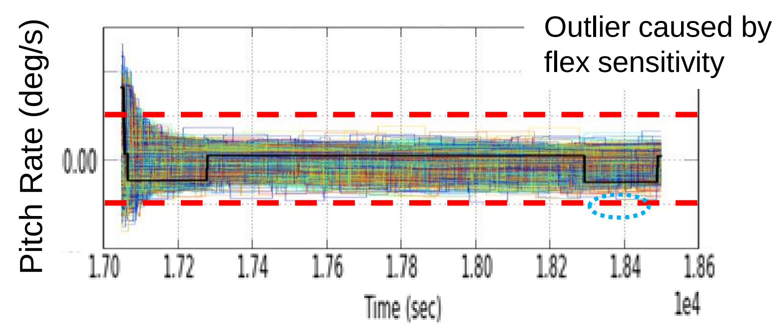
Feed Forward State Estimator (second order Luenberger Observer)



Minimum Impulse with 200ms Wait**



Sub Minimum Impulse with 200ms Wait



Monte Carlo Results Summary

Case	% of Initial Roll Rate Allocation	% of Updated Roll Rate Allocation	% of Initial Pitch/Yaw Rate Allocation	% of Updated Pitch/Yaw Rate Allocation	% of Initial Translational Velocity Allocation	% of Updated Translational Velocity Allocation	% of Baseline Propellant Used
1-Baseline	700%	233%	440%	176%	182%	87%	100%
2-Reduced Lag Filter	500%	167%	310%	124%	120%	57%	31%
3-FFSE	300%	100%	270%	108%	94%	45%	11%
4-Min Impulse (200 ms wait)	170%	57%	100%	40%	92%	44%	7%
6-Sub-Min Impulse (200 ms wait)	95%* / 140%	47%	95%* / 105%	42%	81%	39%	22%
8-FFSE w/ Min Impulse (0 ms wait)	180%	60%	140%	56%	89%	42%	7%

- **Cases 4, 6, and 8 all achieve updated docking error budget (2.5-3.0x initial).**
- **Sub-minimum impulse achieves both allocations, once flex outliers are addressed.**
- **Alternate algorithms drastically reduced propellant usage over the baseline algorithm, with minimum impulse variants using the least propellant.**
- **EUS selected the FFSE with Minimum Impulse (0 ms wait time) for the design.**
  - Has Shuttle flight heritage.[4]
  - Meets the updated allocations with the least propellant usage, and it minimizes the wait period between firings which increases the disturbance rejection capability.

Conclusions

- The sub-minimum impulse algorithm provides the lowest body rates of the analyzed control modes in Monte Carlo cases.
- Investigations show excess propellant usage is not a significant concern.
- Robustness against potential flexible body interaction is a significant concern, yet time domain Monte Carlo simulations demonstrate good response.
- Refinements to the RPOD requirements for the impacted mission show that the minimum impulse mode, feed forward state estimator, and a combination of those are sufficient to robustly achieve requirements. Therefore, the sub-minimum impulse is not needed for the baseline design.
- However, sub-minimum impulse shows promise where further reductions in body rates are desired for a particular vehicle configuration, with only a modest impact to complexity and propellant usage.

Backup

References

1. "Design and Stability of an On-Orbit Attitude Control System Using Reaction Control Thrusters," GN&C Conference, AIAA SciTech 2016, Hall R., Hough S., Orphee C., Clements K., January 4-8, 2016.
2. "International Docking System Standard (IDSS) Interface Definition Document (IDD) Rev. E," NASA, International Space Station (ISS) Multilateral Control Board (MCB), October 2016, Table 3.3.1.1-2.
3. "Performance Comparison of Apollo and AAP CSM RCS DAP State Estimation Schemes", Project Apollo Internal Note MSC-EG-69-46, Edward T. Kubiak, November 25, 1969.
4. "Space Shuttle Orbiter Operational Level C Functional Subsystem Software Requirements (FSSR) Guidance Navigation and Control Part C, Flight Control Orbit DAP", Prepared by the Boeing Company, STS-83-0009-30, December 14, 2000.

Figure 3.3.1.1-2 Coordinate System of Docking Objects (Active and Passive)

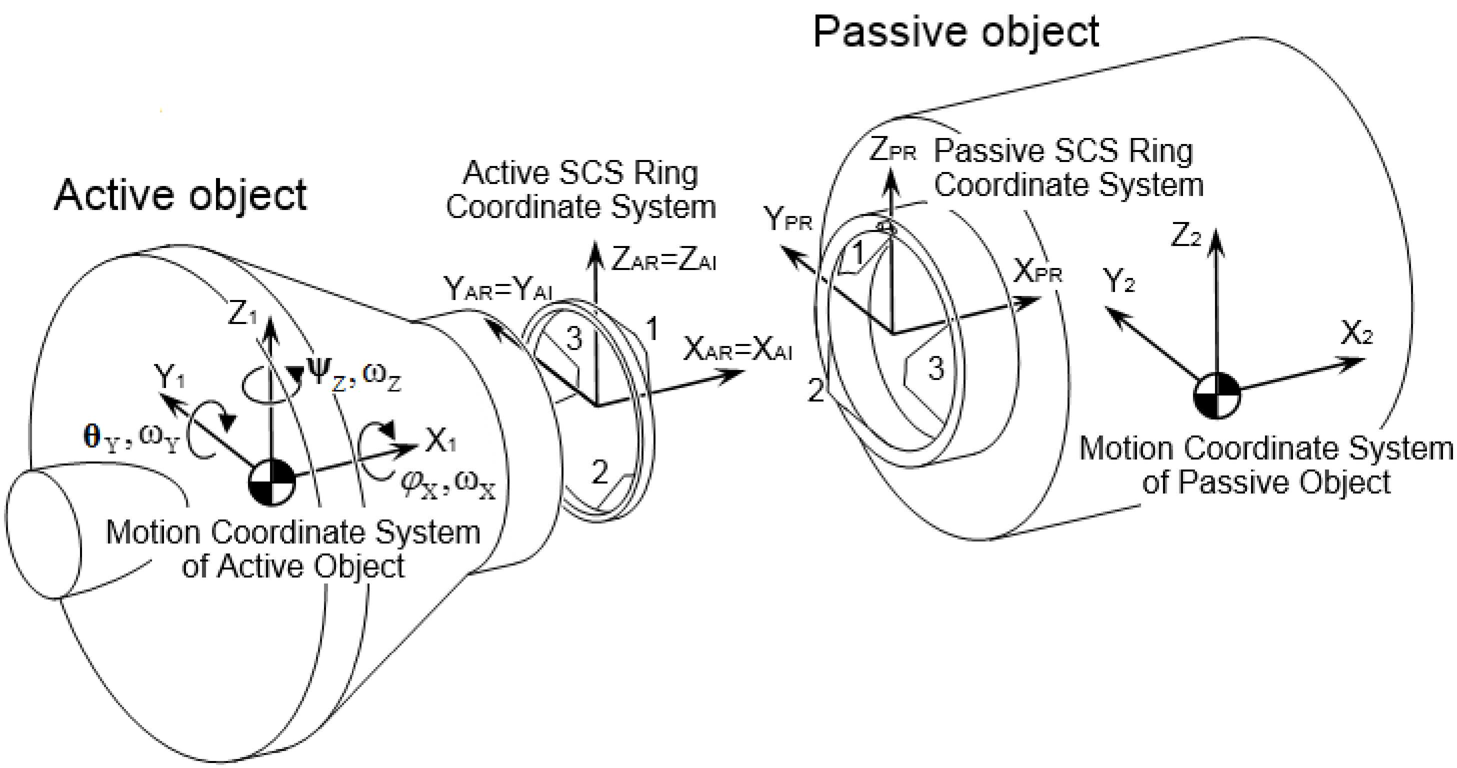


Table 3.3.1.1-2 Initial Contact Conditions

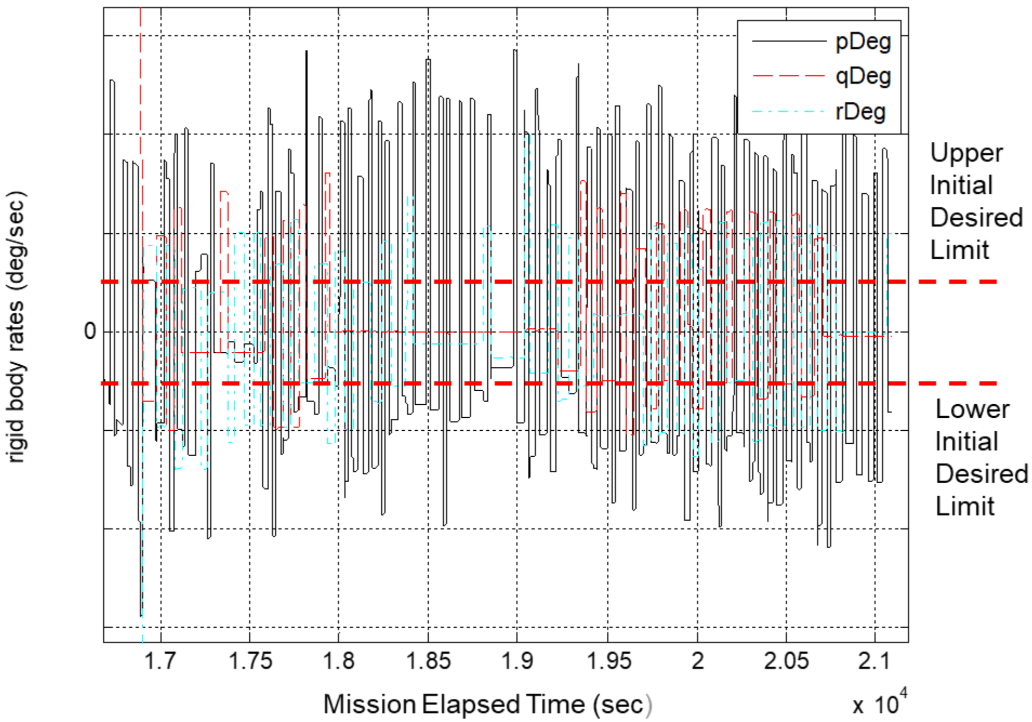
Initial Condition	Limiting Value
Closing (axial) rate	0.05 to 0.10 m/sec
Lateral (radial) rate	0.04 m/sec
Pitch/Yaw rate	0.20 deg/sec (vector sum of pitch/yaw rate)
Roll rate	0.20 deg/sec
Lateral (radial) misalignment	0.10 m
Pitch/Yaw misalignment	4.0 deg (vector sum of pitch/yaw)
Roll Misalignment	4.0 deg

Notes:

1. Initial contact conditions are independent and are to be applied simultaneously, with the exception that the lateral rate at the vehicle cg resulting from the combination of lateral (radial) rate and the pitch/yaw angular rate should not exceed the lateral (radial) rate limit.
2. Mean closing (axial) rate may be adjusted depending on vehicle mass combinations. Refer to Table 3.3.1.2-1.
3. Post contact thrust may be used to achieve necessary capture performance.
4. Lateral (radial) misalignment is defined as the minimum distance between the center of the active soft capture ring and the longitudinal axis of the passive soft capture ring at the moment of first contact between the guide petals.

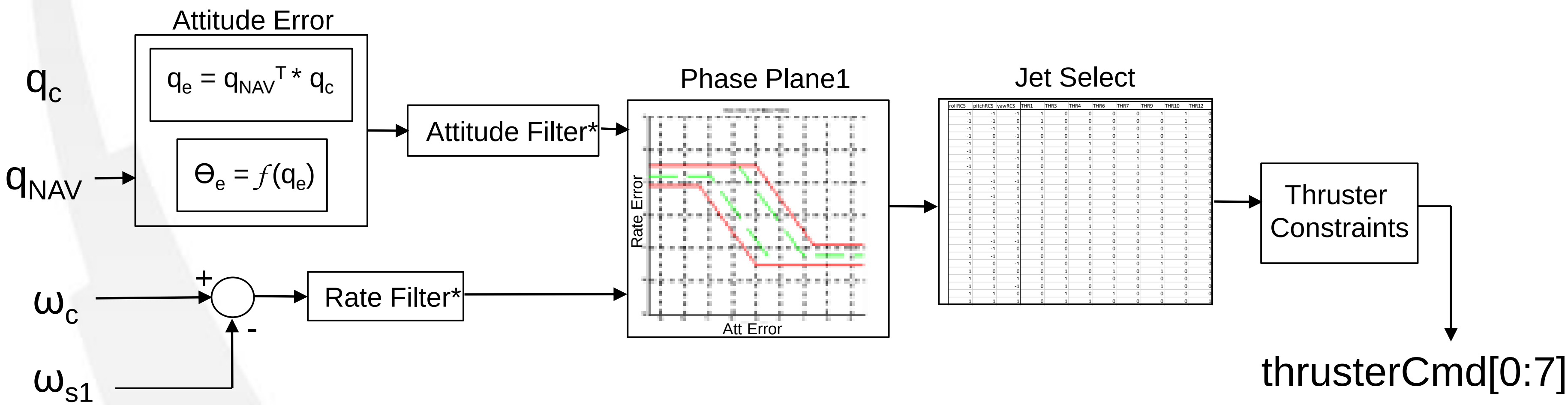
Baseline Algorithms and Docking Allocations

- **During docking, the MPCV is the active vehicle, while the EUS is the passive vehicle performing an attitude hold.**
- **Phase plane control is used for each attitude axis.[1]**
- **Phase plan parameters are time segment based.**
- **International Docking System Standard[2] requirements during docking**
  - Relative rotational rates between active and passive vehicles
    - < 0.2 deg/s in roll, and
    - < 0.2deg/s for the vector sum of pitch/yaw,
  - Relative translational rate < 0.131ft/s (0.04m/s), and
  - Relative angles < 4.0deg.
- **EUS and Orion were assigned portions of these values, so that relative values could be met.**
- **Baseline nominal phase plane results greatly exceeded initial allocations!**



Baseline Algorithm Limitations

- **The baseline algorithm relies on feedback from sensors to determine state changes and make decisions on turning thrusters On/Off.**
- **For this algorithm, the min rate achievable is limited by the max of these constraints:**
  - Thruster minimum impulse or firing duration, and
  - Control loop latency (Sensors, Bus, Flight Control System (FCS) / Flight Software (FSW), Hardware Controllers, Flex Filters).



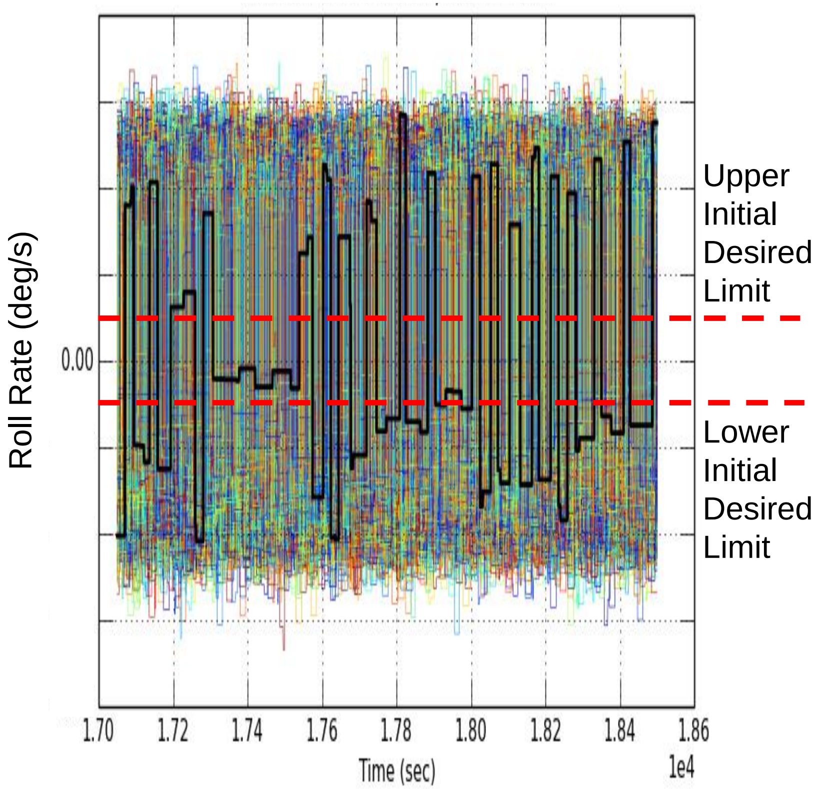
*two 4th order cascaded flex filters

Monte Carlo Runs – Over 1500 Dispersed Variables in MAVERIC

- Mass properties (masses, inertias, CGs),
- Flex (frequencies, damping, gains),
- Slosh (masses, frequencies, damping),
- Sensors (alignment, locations, parameters),
- Stage alignments (X, Y, Z),
- Venting/ (force, direction, flow rate), and
- Thrusters (alignment, pressure drops, max thrust, thrust factor).

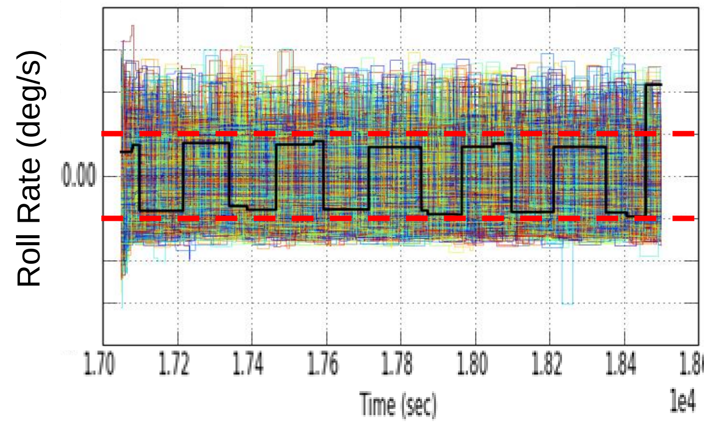
Monte Carlo* Results for 4 of the Control Options Considered – Roll Rate

Standard Phase Plane – Original Baseline

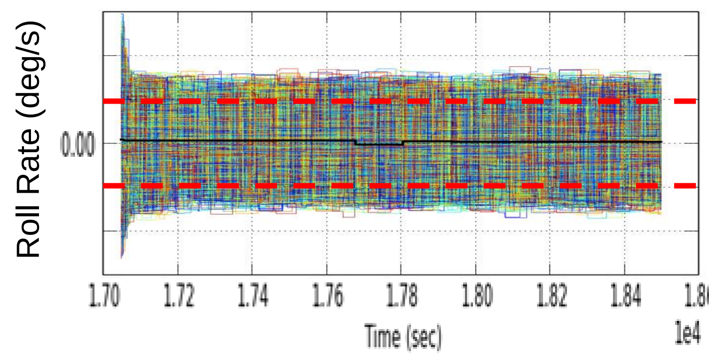


1400s+ of attitude hold with "fine" control system

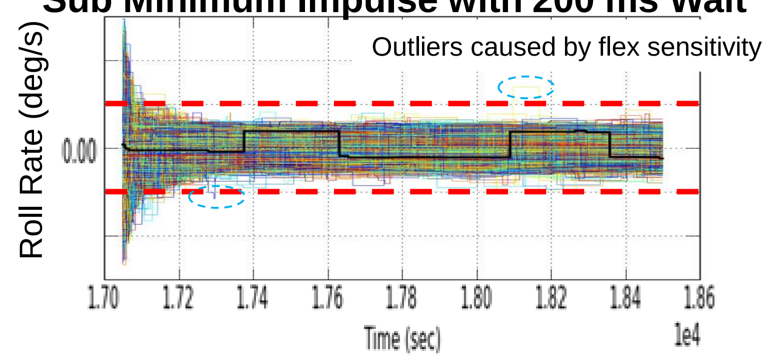
Feed Forward State Estimator



Minimum Impulse with 200 ms Wait**

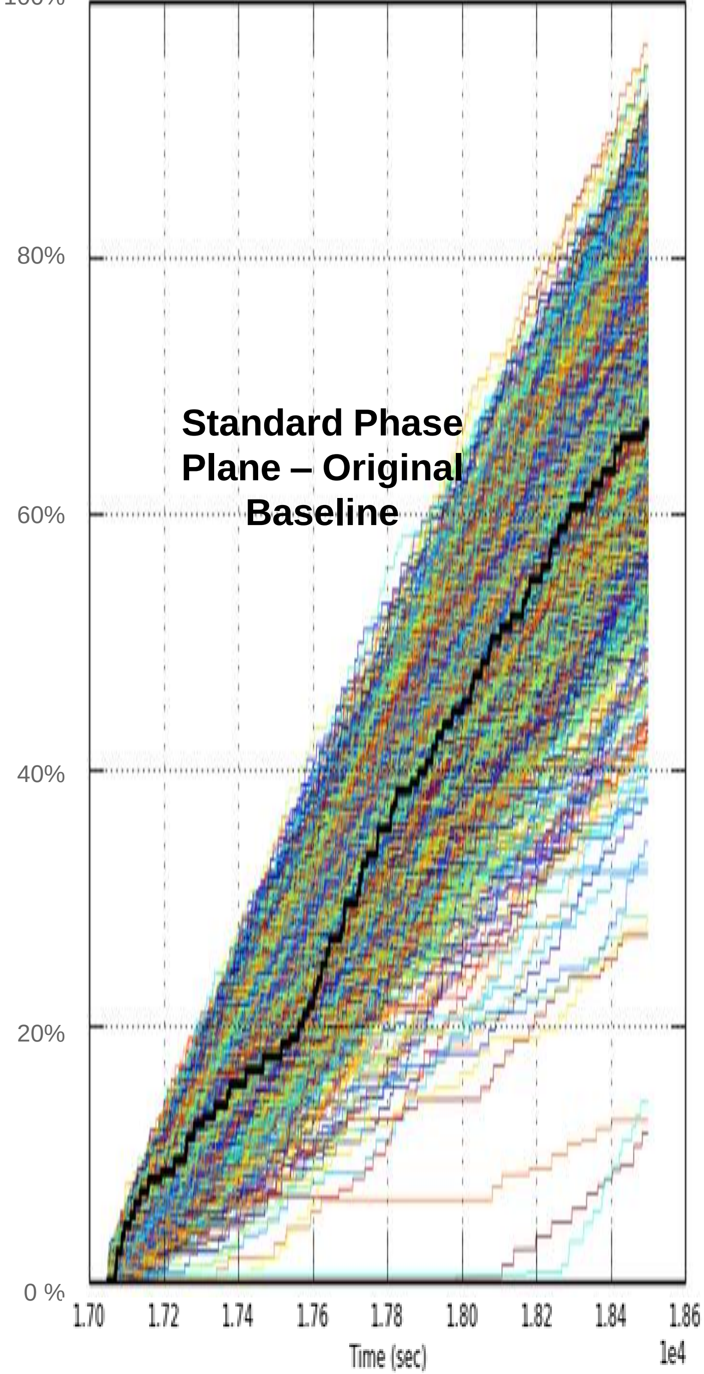


Sub Minimum Impulse with 200 ms Wait



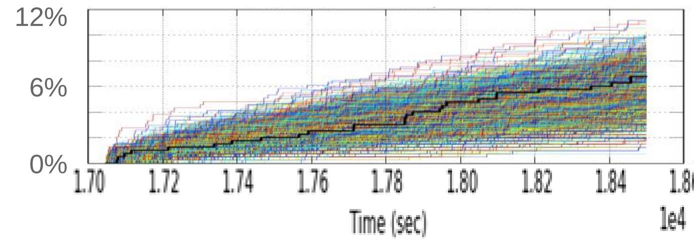
* 2000 runs were executed per case in the Marshall Aerospace Vehicle Representation in C (MAVERIC) modeling and simulation tool.
**Results were very similar for roll, pitch, and yaw for a combined Feed Forward State Estimator with Minimum Impulse with 0ms wait time. The 0 ms wait time allows for quicker response in the presence of disturbances.

Monte Carlo Results for 4 of the Control Options Considered - Prop Usage

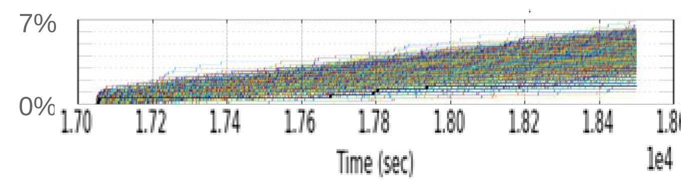


Sub-Minimum Impulse prop usage is more than State Estimator and Minimum Impulse, but still much reduced from original phase plane only method!

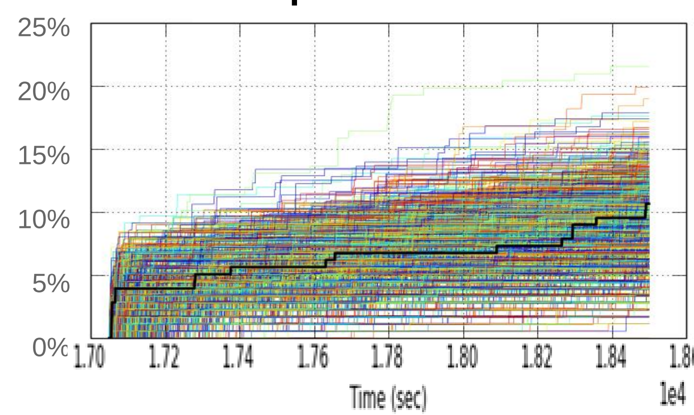
Feed Forward State Estimator (second order Luenberger Observer)



Minimum Impulse with 200 ms Wait



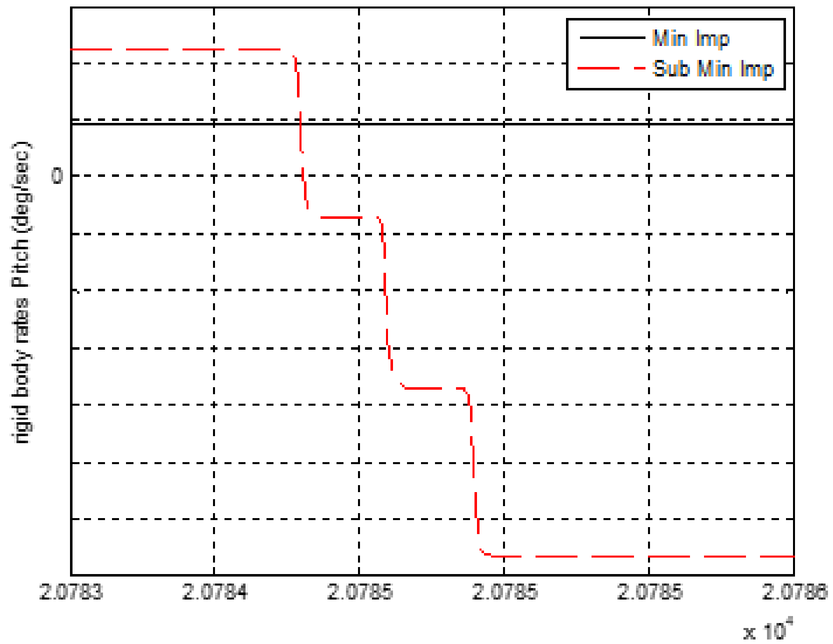
Sub Minimum Impulse with 200 ms Wait



Plots are scaled based on 100% as the top of the original phase plane plot.

Concerns with Sub-Minimum Impulse

- **Some potential concerns with sub-minimum impulse are:**
  - Prop Usage,
  - Disturbance Rejection / Control authority,
  - Rates near filtered signal noise limits causing extra firings,
  - Stability, and
  - Flex interaction.
    - There were 2 outliers in roll and 1 in pitch that exceeded the initial angular rate allocations.
    - Except for the outliers, all the rest of the runs in were below the threshold and well below the threshold in yaw.
    - Adaptive phase plane can reduce the outliers.



Sub Min Impulse Pitch/Yaw rate gave small increments of with each firing in the nominal case.