

# **In-Flight Tuning of the Cassini RCS Attitude Controller**

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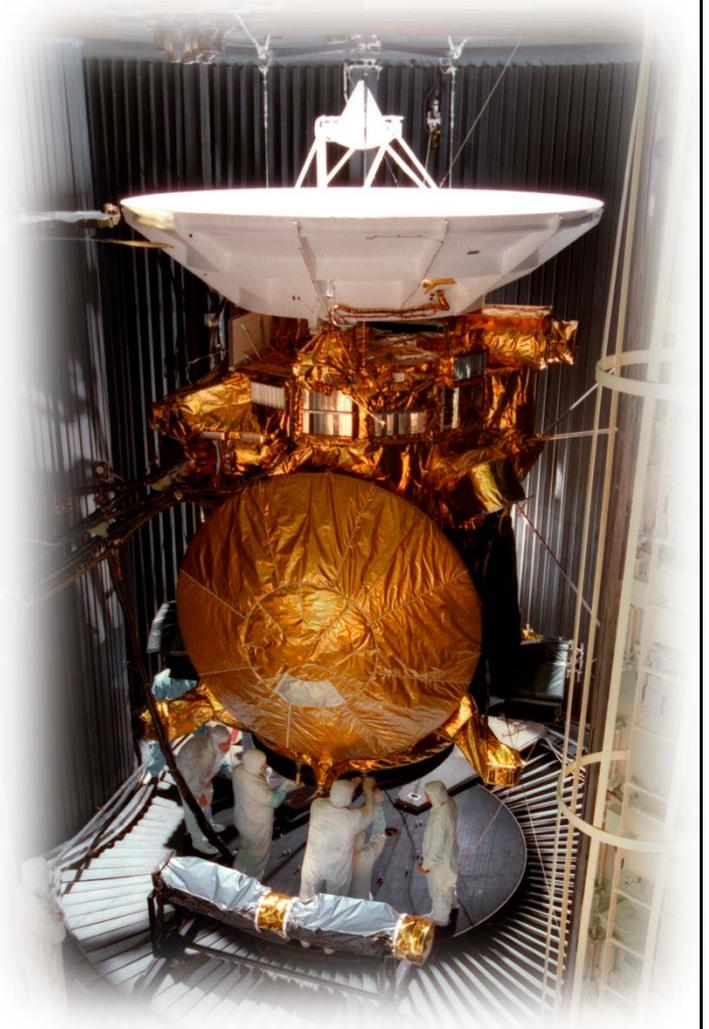
**Jet Propulsion Laboratory,  
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# Overview

- The Cassini Spacecraft
- RCS Controller
- Dynamics Simulation in FSDS
- Testing Parameter Changes
- Summary of In-Flight Tuning
- Conclusions

# The Cassini Spacecraft

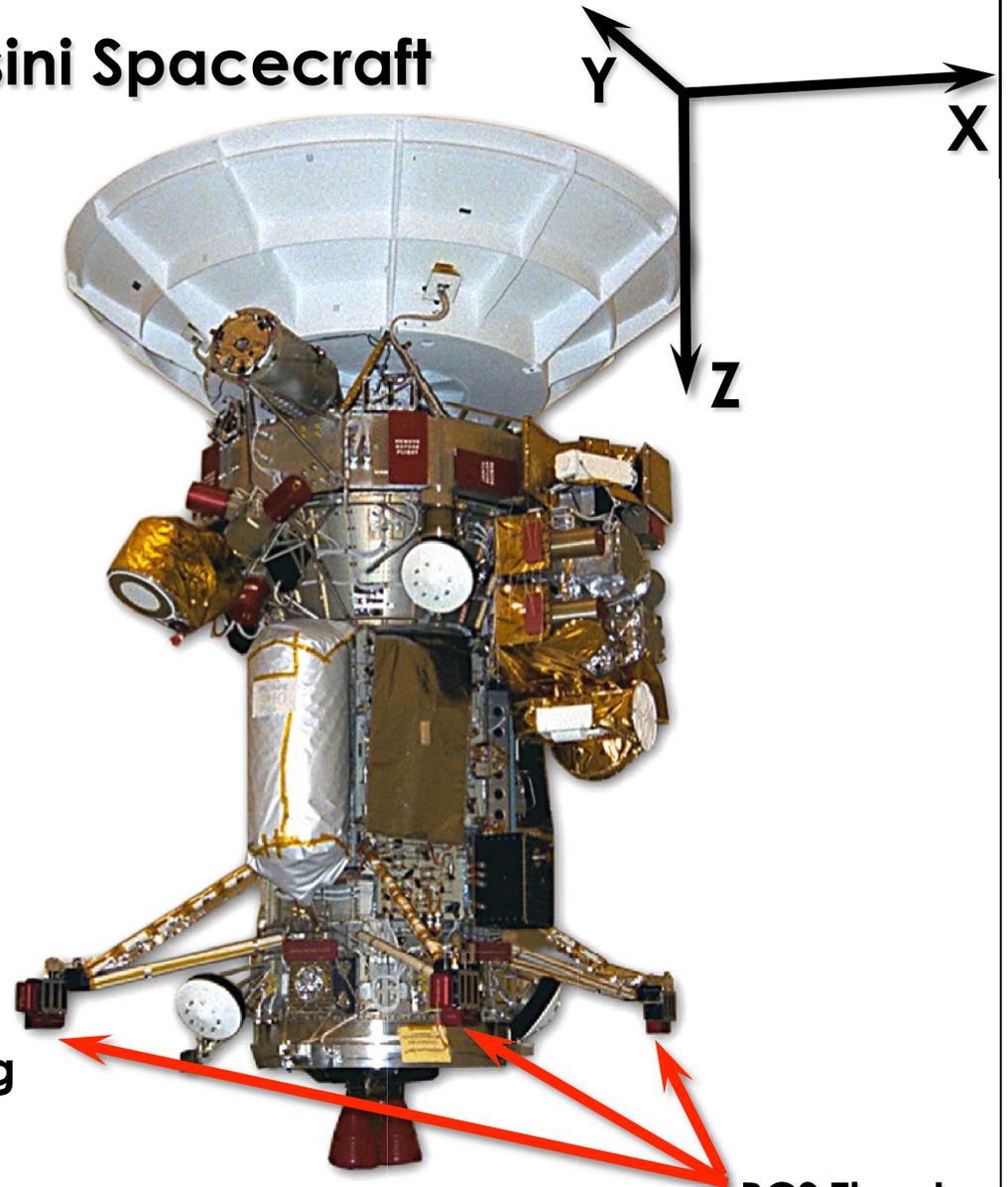
- Launched in 1997
- Arrived at Saturn in 2004
- 2<sup>nd</sup> Extended Mission scheduled to last until 2017
- 12 major science instruments
- Must slew to point science instruments
- 3-Axis stabilized and two sources of attitude control: RCS thrusters and reaction wheels



Credits: NASA, JPL

# The Cassini Spacecraft

- RCS Thrusters
  - Two fully redundant thruster branches (A & B)
  - Y1-Y4 have Z-axis control authority
  - Z1-Z4 have X & Y axis control authority
- Degradation in multiple A-Branch Z-facing thrusters led to swap to backup hardware
- **To preserve health of B-branch thrusters and to conserve hydrazine, several attitude control logic (ACL) parameters are examined for in-flight tuning**



Credits: NASA, JPL

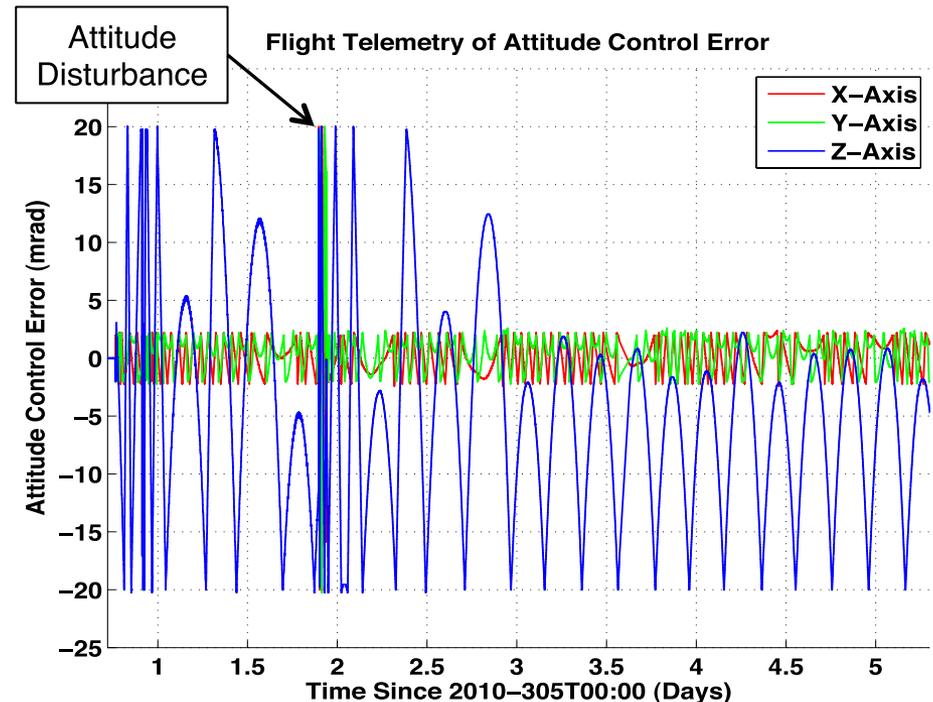
**RCS Thrusters**

## RCS Controller

- Two RCS control modes on Cassini: High-Rate mode and Low-Rate mode
- High-Rate Mode
  - Standard bang-bang controller
  - Used for slews, orbit trim maneuvers, RWA momentum biases, and for strong external torques (i.e. Titan's atmosphere and Enceladus' ice plume)
  - Uses only 0.125 sec thruster pulses (or multiples of 125 ms)
  - Control deadband typically 2 mrad (0.11 deg) for X & Y axes and 2-20 mrad for the Z-axis

# RCS Controller

- Low-Rate Mode
  - Used while Cassini is quiescent for long periods
  - Adaptive Pulse Width Logic used to fine-tune pulse duration based on position error behavior
  - Controller attempts to achieve one-sided limit cycling
  - Thruster pulse duration varies autonomously between 7 ms and 125 ms

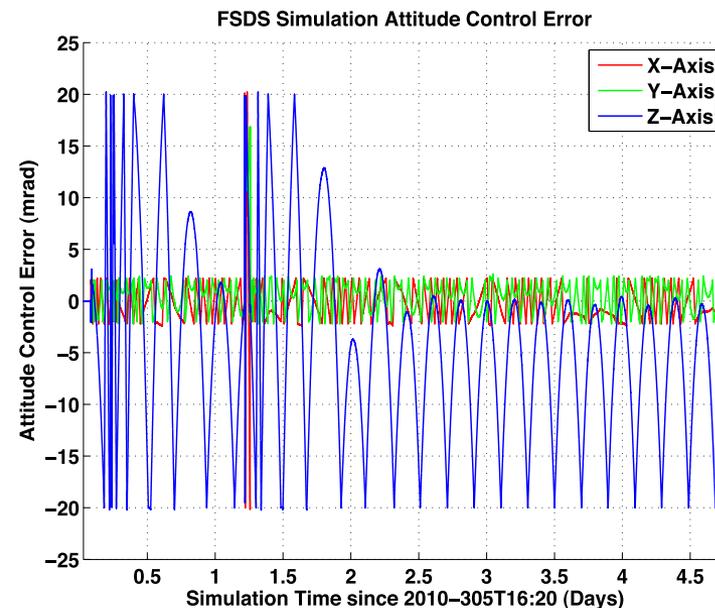
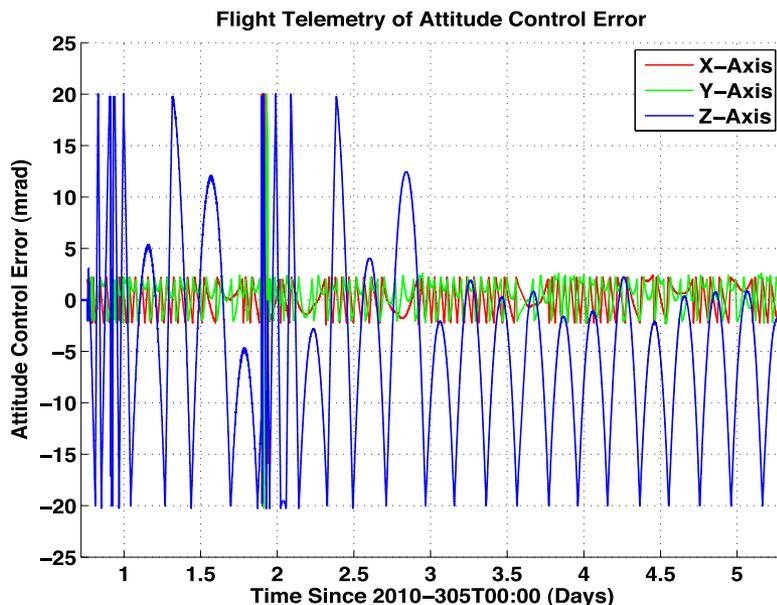


# Purpose

- Examine whether ACL parameter changes improve controller performance
  - Improvement metrics: thruster on-time, thruster on/off cycles, and hydrazine consumption
- RCS parameters examined in this investigation
  - High-Rate to Low-Rate Persistence Timer
  - “Factor Next Limit Cycle”
  - Minimum RCS Pulse Width
  - Additional parameters are discussed in the paper:
    - Walking Deadband Number of Steps Allowed
    - Walking Deadband Step-Size
    - X & Y axis deadband limits

# Testing Parameter Changes

- Parameter changes tested on the ground using FSDS
  - FSDS is the Flight Software Development System
  - Runs full attitude control flight software and simulates spacecraft environment in high fidelity
  - FSDS simulation ~10x faster than real-time. Tuning FSDS required ~120 days of simulation time.
  - Simulation parameters for external torque and thruster performance tuned to match recent flight telemetry

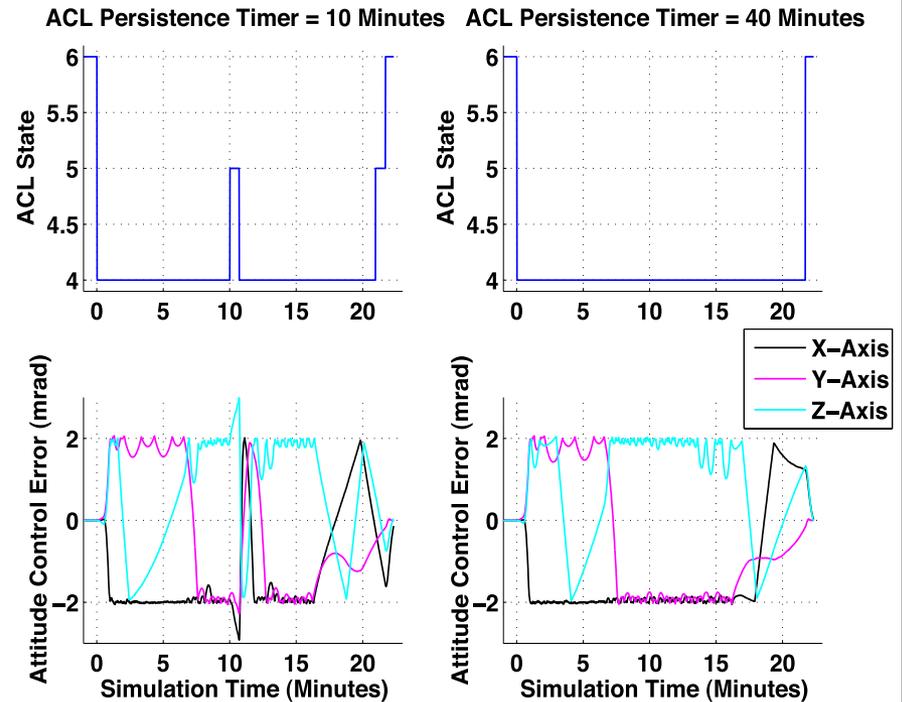


# Parameters to Examine

- **High-rate to Low-rate persistence timer**
- “Factor Next Limit Cycle”
- Minimum RCS Pulse Width
- Additional parameters are discussed in the paper:
  - Walking Deadband Number of Steps Allowed
  - Walking Deadband Step-Size
  - X & Y axis deadband limits

# High-Rate to Low-Rate Persistence Timer

- Cassini autonomously switches from high-rate to low-rate mode
  - Transition occurs after a timer expires if rate errors and commanded turn rates are both small
  - From 1997 until 2011, timer value: 10 min
- ACL mode transition during RWA momentum bias is undesirable
  - RWA biases frequently last longer than 10 minutes
  - Low-rate mode insufficient to control attitude error during RWA bias
  - Unnecessary transition requires more hydrazine and thruster cycles than staying in high-rate mode
- Proposed Timer Change: From 10 min to 40 min
  - Change decreases hydrazine consumption by 10% per bias
  - Cassini has performed 350 RWA biases since July 2008. Savings are significant.



ACL State Key:

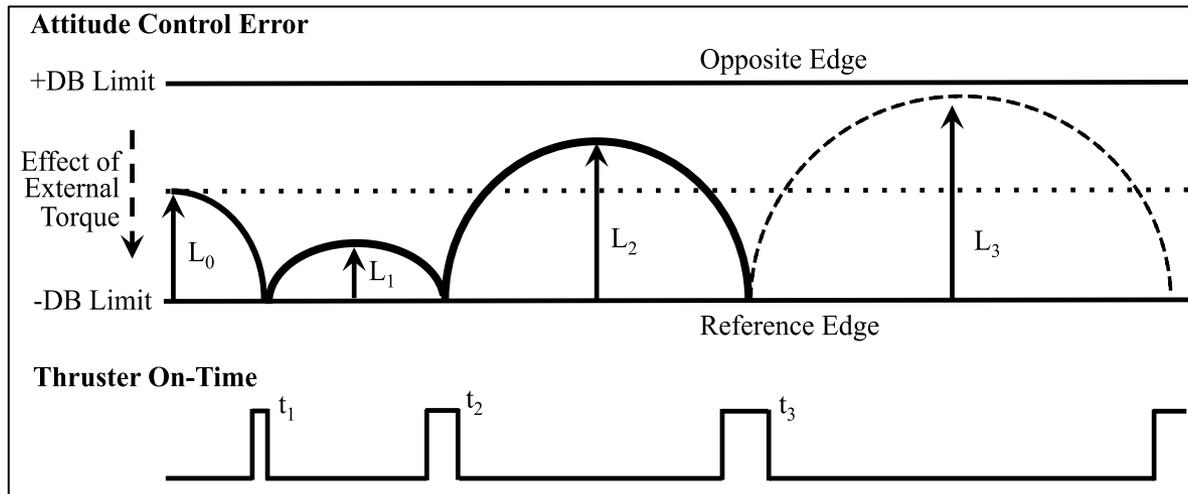
- 6 = RWA Control Mode
- 5 = Low-Rate RCS Mode
- 4 = High-Rate RCS Mode

# Parameters to Examine

- High-rate to Low-rate persistence timer
- **“Factor Next Limit Cycle”**
- Minimum RCS Pulse Width
- Additional parameters are discussed in the paper:
  - Walking Deadband Number of Steps Allowed
  - Walking Deadband Step-Size
  - X & Y axis deadband limits

## “Factor Next Limit Cycle” Parameter

- Parameter used in adaptive pulse width logic
- Sets the one-sided deadband “target distance” to traverse

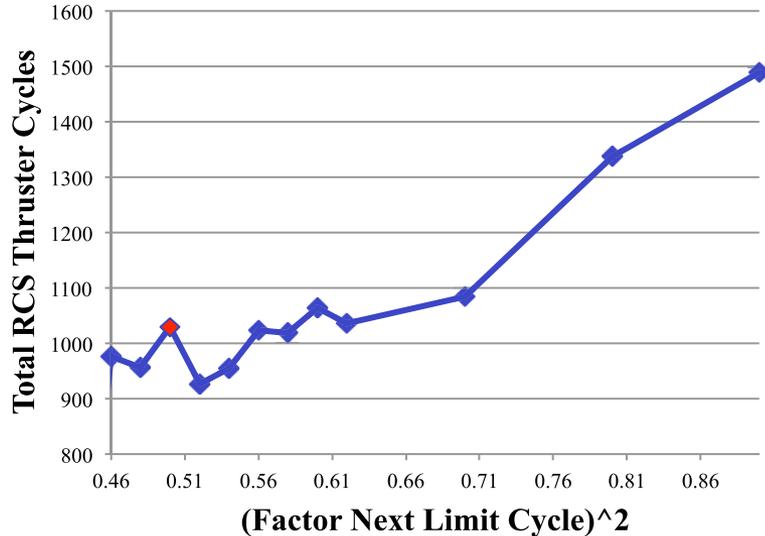


$$t_3 = \left( \frac{\sqrt{L_2} + \sqrt{L_3}}{\sqrt{L_1} + \sqrt{L_2}} \right) \times t_2$$

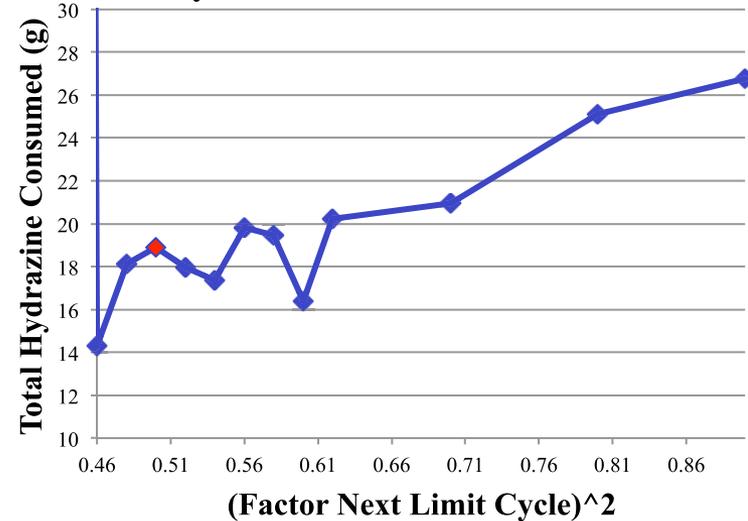
- “Factor Next Limit Cycle” =  $\sqrt{L_3}$
- Currently parameter is  $\sqrt{0.5}$ , from 1997-2000 it was  $\sqrt{0.75}$

# “Factor Next Limit Cycle” Parameter

Total RCS Pulses vs. FNLC Value



Hydrazine Use vs FNLC Value



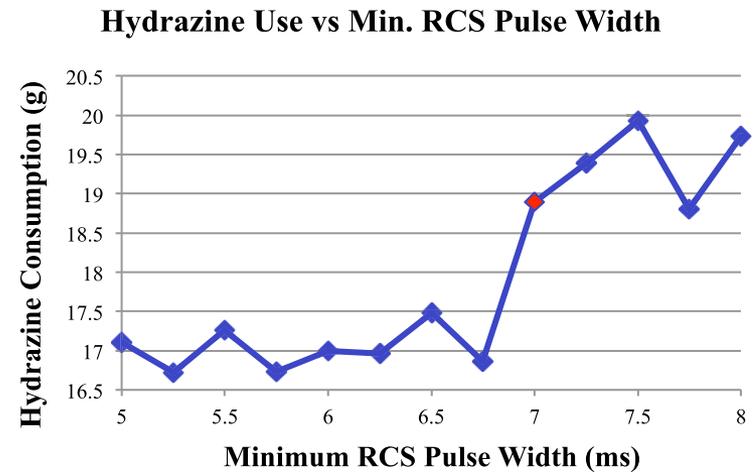
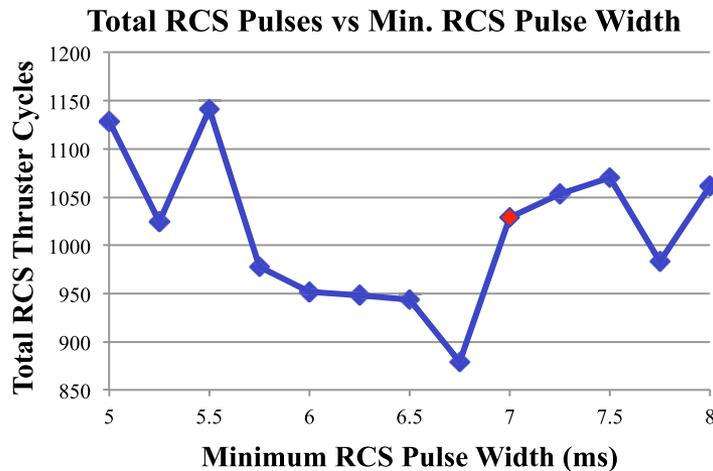
- Controller unstable for FNLC values below  $\sqrt{0.46}$
- Hydrazine consumption and total RCS pulses increase for FNLC values larger than  $\sqrt{0.5}$
- Conclusion: There is no benefit in changing this parameter

# Parameters to Examine

- High-rate to Low-rate persistence timer
- “Factor Next Limit Cycle”
- **Minimum RCS Pulse Width**
- Additional parameters are discussed in the paper:
  - Walking Deadband Number of Steps Allowed
  - Walking Deadband Step-Size
  - X & Y axis deadband limits

# Minimum RCS Pulse Width

- FSW limit on minimum RCS thruster pulse is 7 ms
- Cassini thrusters ground tested to 4 ms pulse duration
  - Voyager program uses similar thrusters down to 4 ms



- Summary:

- Reducing min. pulse duration to 5.75-6.75 ms reduces hydrazine consumption and total thruster pulses
- Pulse durations shorter than 5.75 ms increase the total thruster pulses

# Parameters to Examine

- High-rate to Low-rate persistence timer ←
- “Factor Next Limit Cycle” ✗
- Minimum RCS Pulse Width ←
- Additional parameters are discussed in the paper:
  - Walking Deadband Number of Steps Allowed ←
  - Walking Deadband Step-Size ✗
  - X & Y axis deadband limits ✗

← = Parameter Change Improves  
Controller Performance

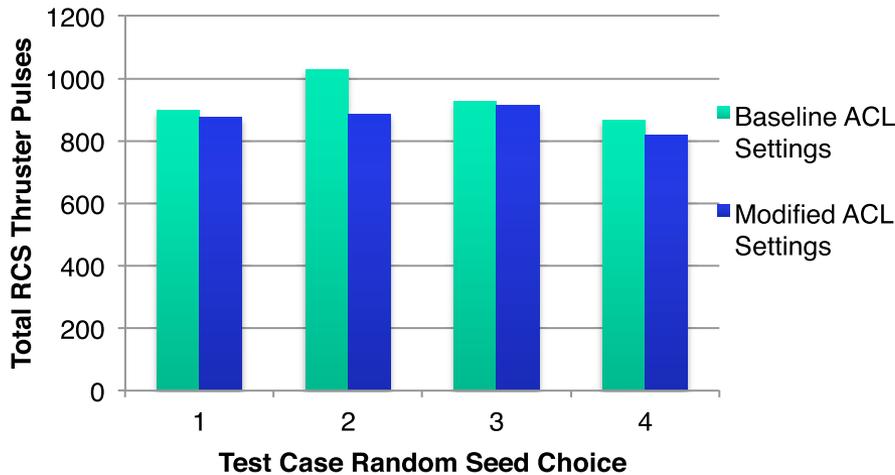
✗ = No Controller Improvement or  
Operational Reasons to Not Change

# Summary of Proposed Changes

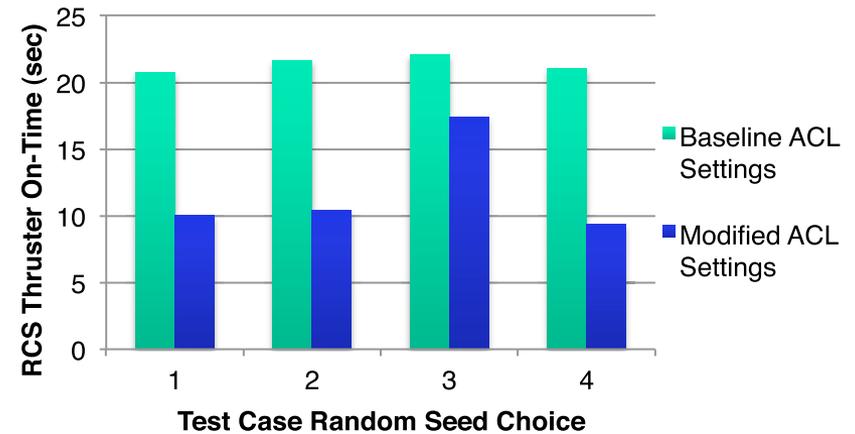
- Increase High-Rate to Low-Rate Persistence Timer from 10 min to 40 min
  - Change decreases bias hydrazine use by 10% on average
  - Improvement is independent of changes to other parameters
- Highest improvement to low-rate ACL behavior by changing:
  - **Minimum RCS Pulse Width:** Decrease from 7 ms to 6 ms
  - **Walking Deadband Steps:** Increase from 5 steps to 7 steps
- Coupling of these changes performs better than only changing one parameter

# Proposed Changes

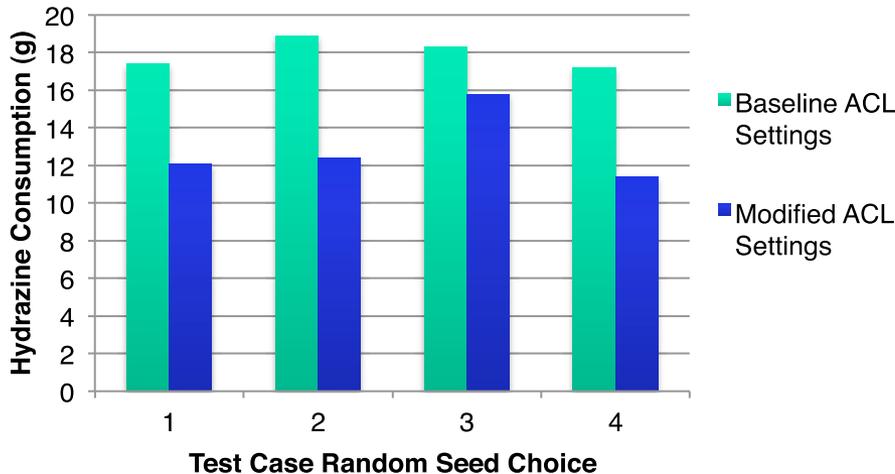
Comparison of Total RCS Thruster Pulses



Comparison of Total RCS Thruster On-Time



Comparison of Hydrazine Consumption



- Proposed Changes:
  - Walking Deadband Steps: Increased from 5 to 7 steps
  - RCS Min. Pulse Width: Decreased from 7 ms to 6 ms
- Summary of Results:
  - Average reduction is from 4 FSDS simulations using different noise seeds
  - Total RCS thruster cycles: **6% reduction**
  - RCS Thruster On-Time: **45% reduction**
  - Hydrazine Consumption: **28% reduction**

# Summary of Proposed Changes

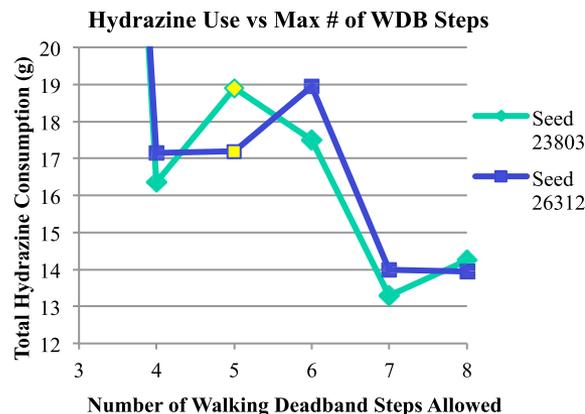
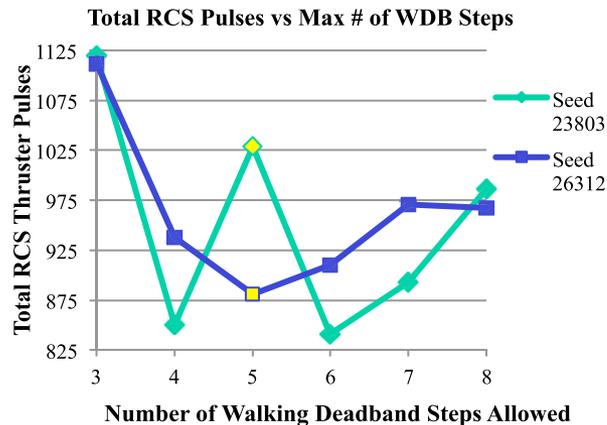
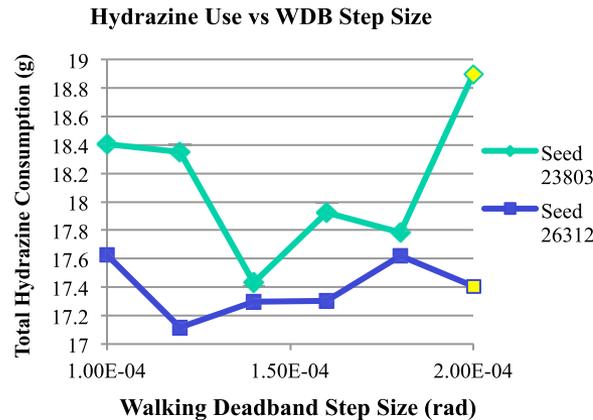
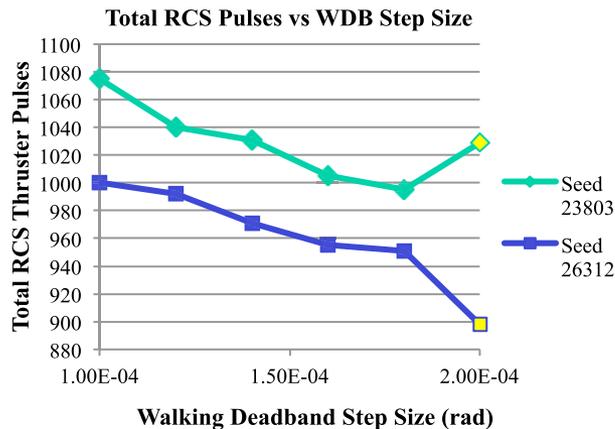
- Simulations suggest that ACL changes decrease consumable use while in low-rate mode
  - Total RCS thruster cycles: **6% reduction** (8 pulses/day reduction)
  - RCS Thruster On-Time: **45% reduction** (1.3 sec/day reduction)
  - Hydrazine Consumption: **28% reduction** (0.70 grams/day reduction)
    - At this rate it would take 50 days of RCS control with the changed parameters to save the equivalent hydrazine of one 35 gram RWA bias
- Nominally Cassini spends very little time in the low-rate RCS mode
- Changes to low-rate RCS parameters has little impact on operational consumable use
- If Cassini loses use of RWA control mode then the savings offered by the parameter changes becomes much more significant

# Conclusion

- Adjusting Cassini ACL parameters can improve controller performance, decrease hydrazine consumption, and protect RCS thruster health
- Changes to 6 ACL parameters investigated
  - Improvement possible by changing 3 parameters:
    - High-Rate to Low Rate Persistence Timer
    - Minimum RCS Pulse Width
    - Walking Deadband Steps (see paper for more information)
- Increasing High-Rate to Low-Rate Persistence Timer from 10 min to 40 min decreases hydrazine consumption by 10%
  - Change made onboard spacecraft on July 7<sup>th</sup>, 2011
- Changes to low-rate ACL parameters present no significant savings for nominal mission
  - RCS Parameter changes may be reconsidered should Cassini ever lose use of the RWA control mode

# Backup Slides

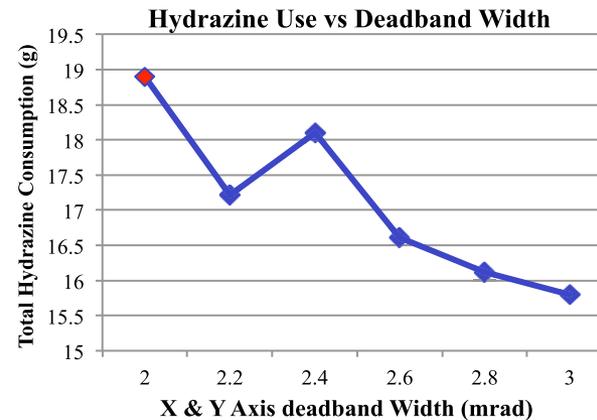
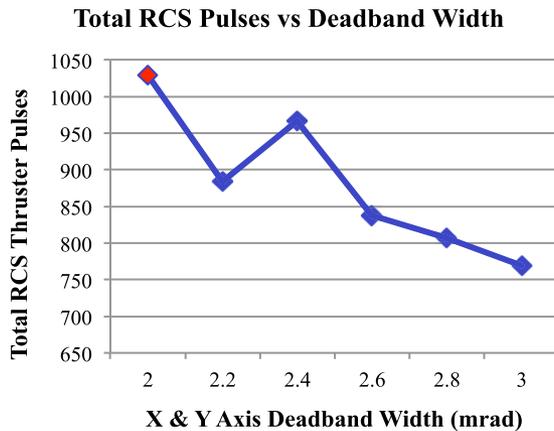
# Walking Deadband Parameters



- Walking Deadband allows position error to “walk” slightly above deadband limit by integer number of steps of a fixed step width
- No obvious improvement by decreasing WDB step size
- Increasing number of steps from 5 to 7 improves RCS performance

# Deadband Limit

- Cassini nominally does not increase the X & Y axis deadbands beyond 2 mrad to avoid interfering with HGA use
- If Cassini were to spend significant periods of time on RCS control then data relay impact may be justified to decrease thruster use and hydrazine consumption

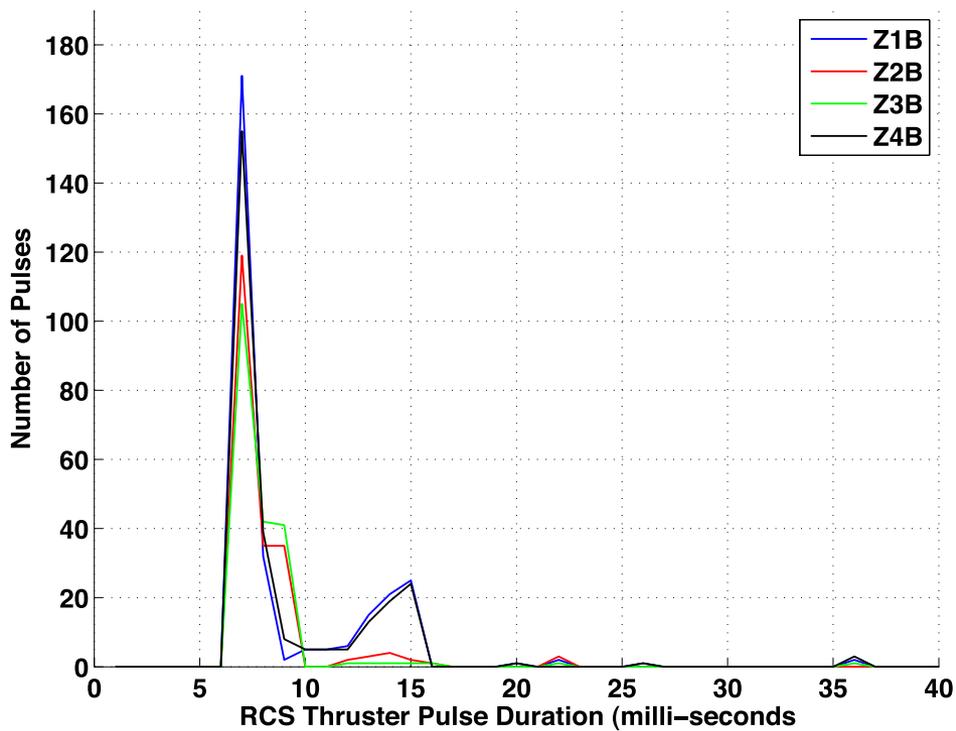


- Summary:
  - ~25% reduction in thruster cycles and a ~15% reduction in hydrazine use by increasing deadband width to 3 mrad
  - Operationally, this savings is not worth the impact to HGA data relay

Baseline FSDS Case  
 (No ACL Modification)

FSDS Case with  
 proposed ACL Changes

Z-Thruster Pulse Duration Breakdown



Z-Thruster Pulse Duration Breakdown

