Thruster-Specific Force Estimation and Trending of Cassini Hydrazine Thrusters at Saturn

Joan Stupik
Thomas A. Burk

Cassini Spacecraft Operations Office
Jet Propulsion Laboratory
California Institute of Technology

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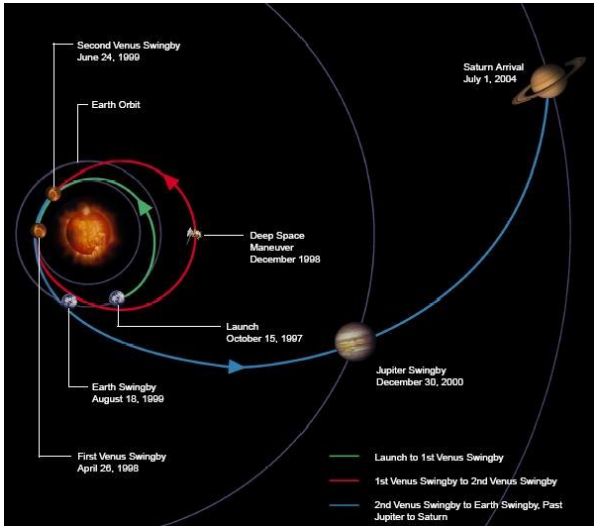
Cassini Spacecraft

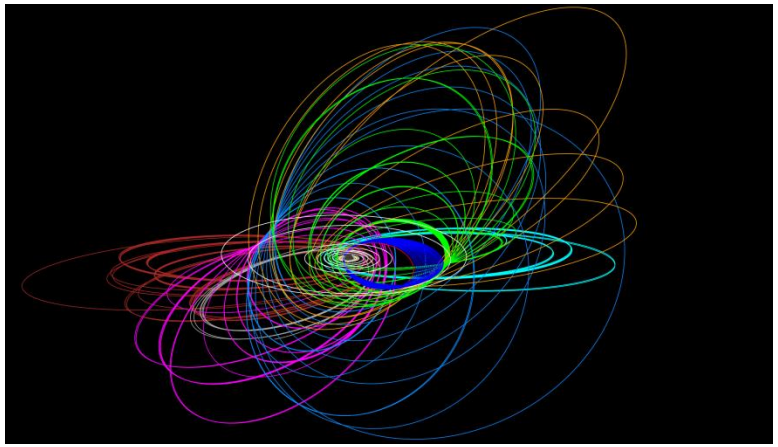
From NASA/JPL Cassini website

- General spacecraft information
  - Main engine: 445 N (2)
  - Launch total mass: 5,574 kg
  - Propellant launch mass: 3000 kg
    - Additional 132 kg hydrazine
  - **Thrusters: 1 N at launch (16)**
    - **Prime set (8)**
    - **Back-up set (8)**
  - Reaction wheels (4)
    - 3 active, 1 back-up

Mission Phases of Cassini



Cruise (1997 – 2004)



Prime Tour (2004 – 2008)

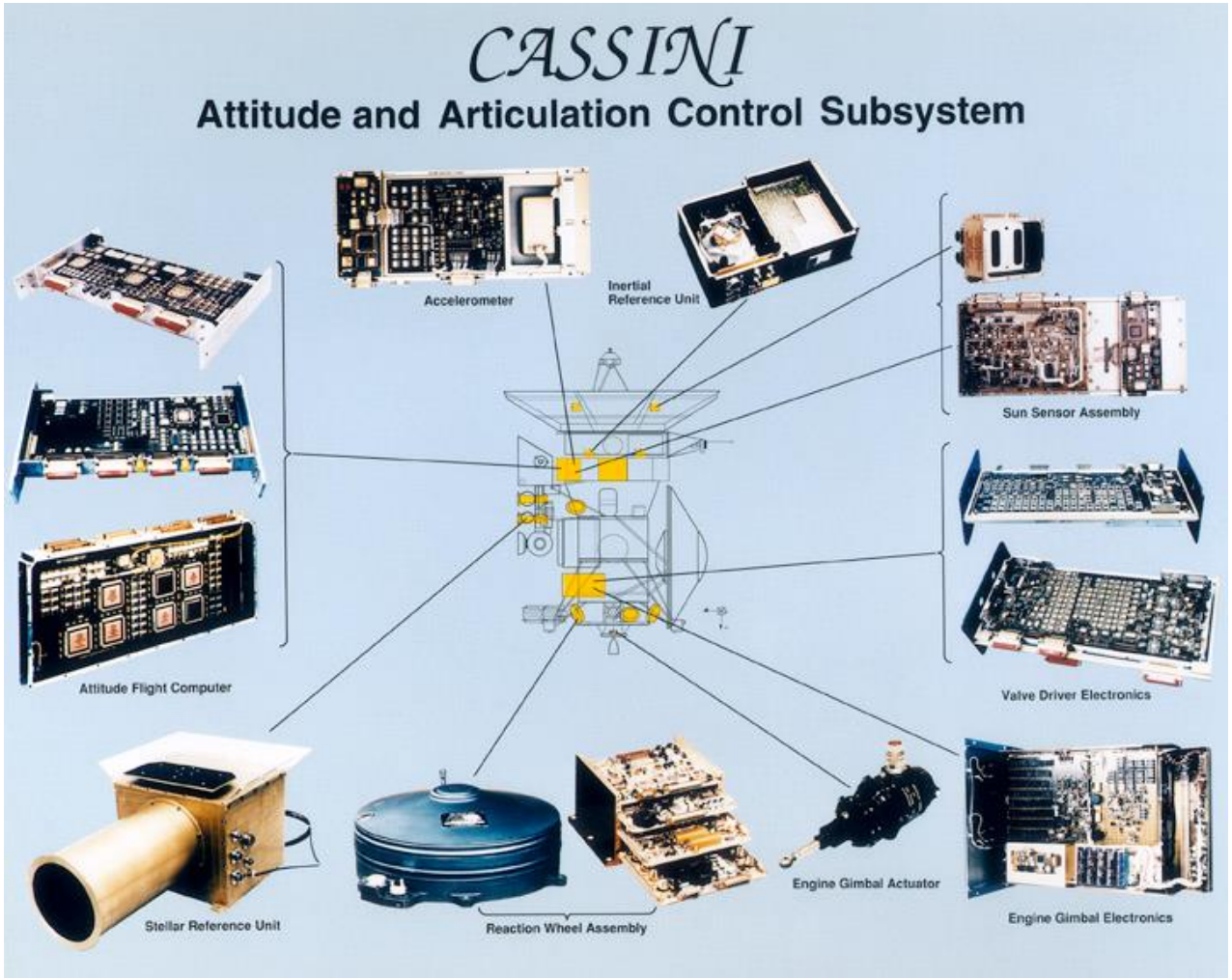
XM Equinox (2008 – 2010)

XXM Solstice (2010 – 2017)

As the spacecraft ages, monitoring hardware health becomes increasingly important

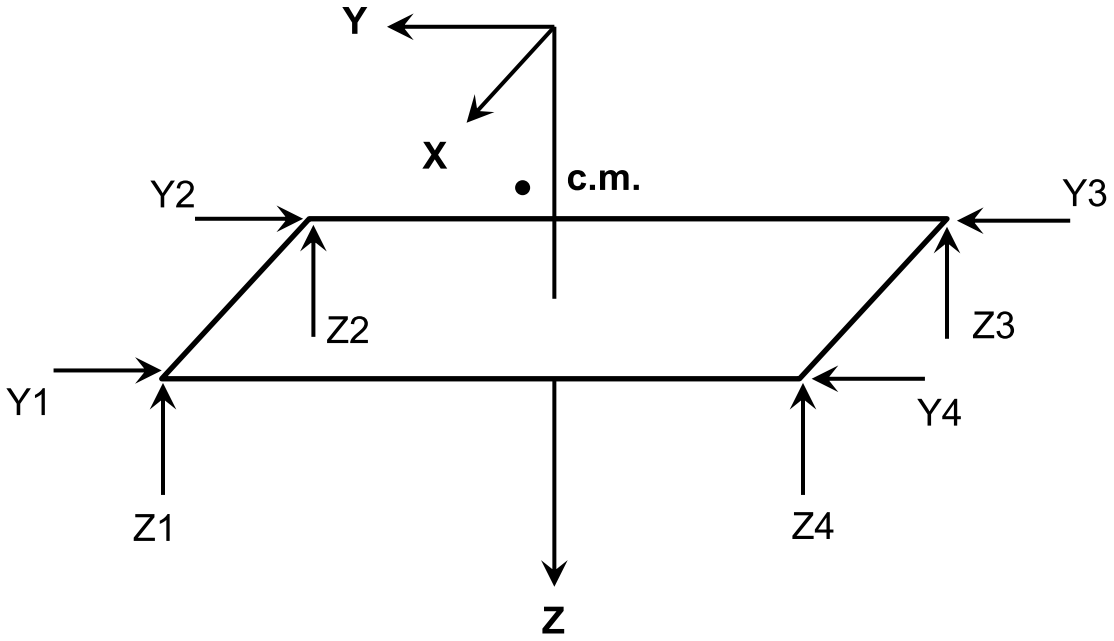
GNC Subsystem

- Calibrations at least once per year for IRUs, gimbals, SRU
- Currently using some back-up hardware:
  - Reaction wheel 4 (RWA4) replaced RWA3 as prime in 2003
  - Thruster branch B (B-branch) replaced A-branch in 2009, due to degradation



From NASA/JPL

Cassini RCS Thruster Branch



- Eight 1-N (0.225 lb) thrusters
- Y-thrusters fire in pairs – no ΔV produced (nominally)
- A-branch and B-branch are almost identical

Torque Axis Needed	+X	-X	+Y	-Y	+Z	-Z
Thrusters to Fire	Z3,Z4	Z1,Z2	Z1,Z4	Z2,Z3	Y2,Y4	Y1,Y3

Thruster Activities

- Cruise phase attitude control
- Orbit trim maneuvers (OTMs)
- Reaction wheel momentum biasing (changing from one momentum state to another)
- Reaction wheel friction characterization tests (not done since 2010)
- Low-altitude Titan or Enceladus flybys to counteract atmospheric torque (rare)
- Special observations when a science team needs to turn quickly (rare)
- Safe mode (rare…hopefully)

Thrust Magnitude Estimation

- There is no direct measure of the thrust produced from each individual thruster

Doppler

- Navigation team is able to determine the average thrust for events whose ΔV is along the Earth line
- Theoretically could fire thrusters individually for thrust magnitude estimation, but never done for Cassini

Thrust Calibration Slews

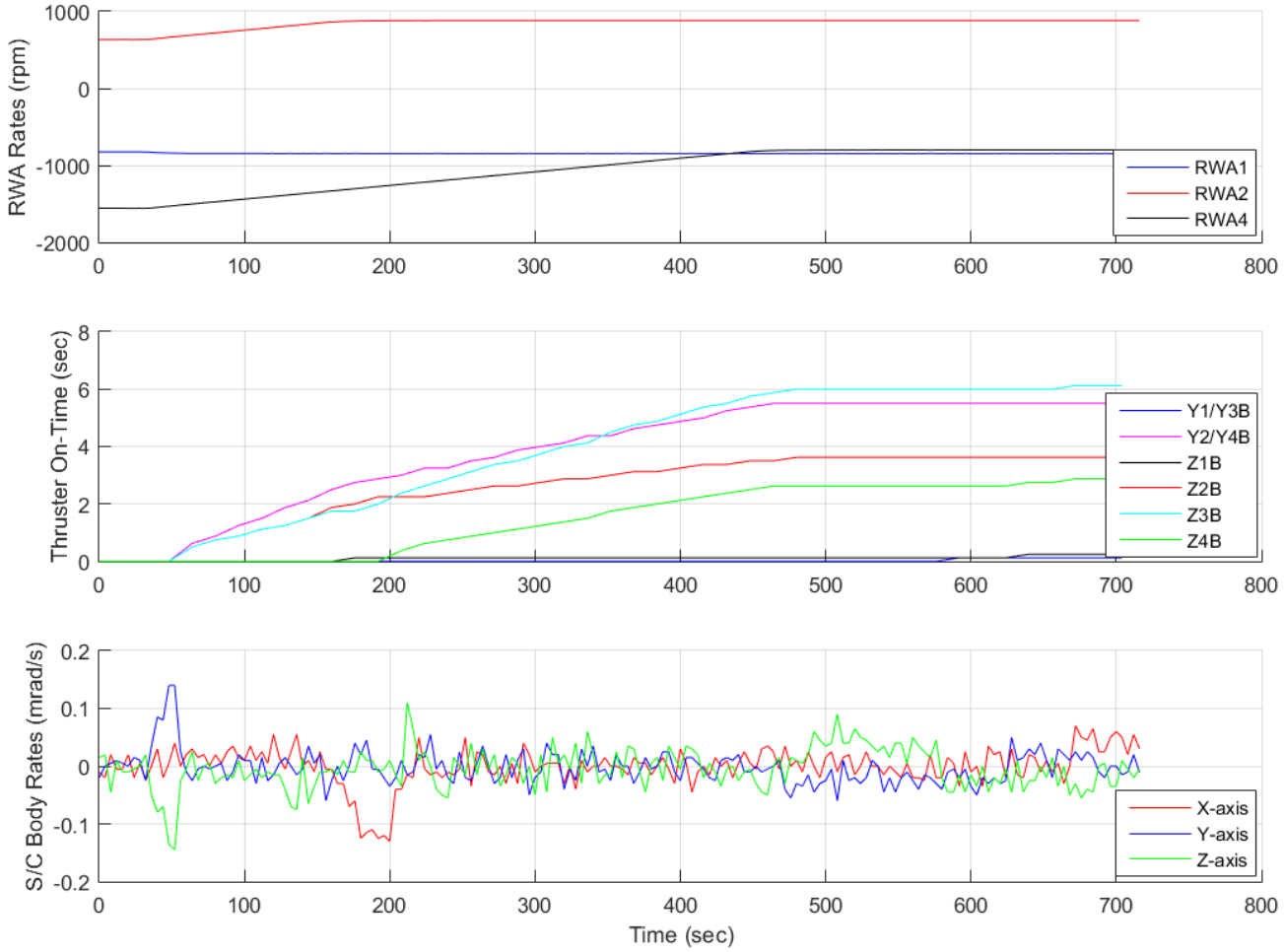
- Slews done using RCS thrusters for the sole purpose of backing out the thrust values
- Costly in terms of hydrazine

Use Existing Thrust Activities

- Specifically, RWA momentum biases
- Biases are the most frequent thrusting event
- Can back-calculate the individual thrust for each Z-facing thruster

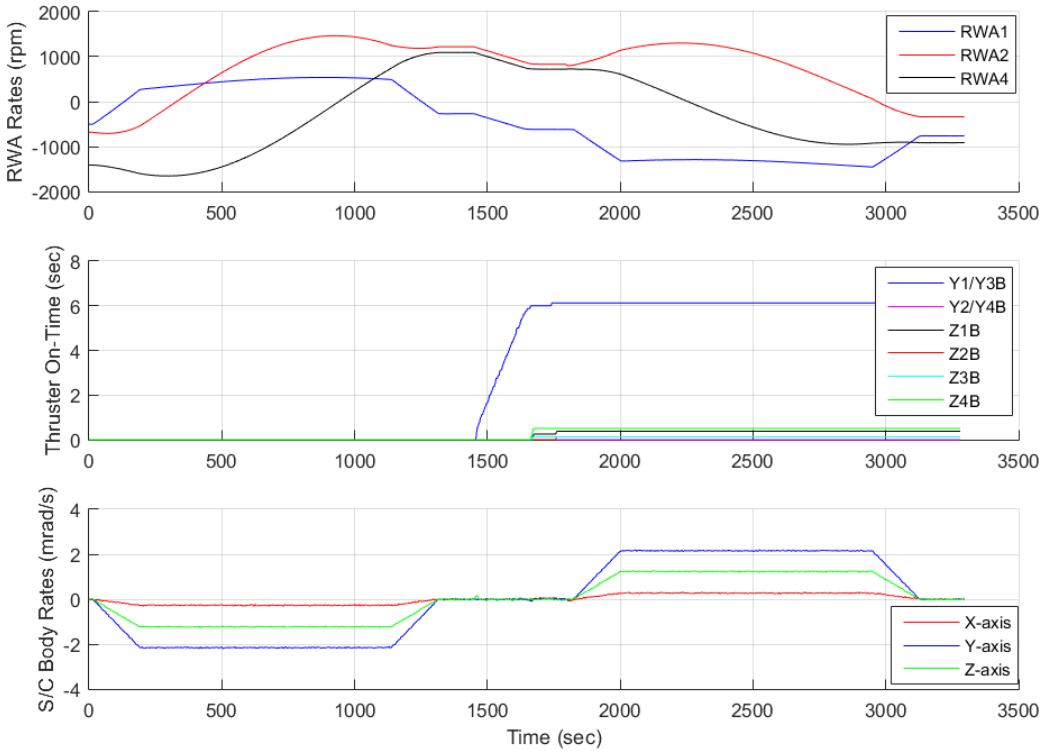
RWA Momentum Biases

- Change reaction wheels from an initial rate to a desired final rate
- Thrusters fire to counteract torque, holds the S/C at a fixed attitude



RWA Momentum Y-Biases

- Purpose: distribute thruster usage more evenly between Y-branch and Z-branch
- Goal: momentum bias the RWAs using only Y-thrusters
- Turn the spacecraft to align the predetermined, desired ΔH vector with the spacecraft Z-axis



Thrust Estimation Algorithm

$$I_{s/c}\dot{\vec{\omega}} + \dot{\vec{H}}_{RWA} + \vec{\omega} \times (I_{s/c}\vec{\omega} + \vec{H}_{RWA}) = \vec{\tau}_{net}$$

$$\downarrow \int_{t_1}^{t_2}$$

$$I_{s/c}\Delta\vec{\omega} + \Delta\vec{H}_{RWA} + \int_{t_1}^{t_2} \vec{\omega} \times (I_{s/c}\vec{\omega} + \vec{H}_{RWA})dt = \int_{t_1}^{t_2} \vec{\tau}_{net}dt$$

- Euler's rigid body dynamics equation (in spacecraft body frame)
- Assumptions
  - Only significant external torque comes from thrusters
  - Mechanical misalignments are negligible
  - Products of inertia, center of mass and thrust magnitude do not change over a small thruster event
  - Products of inertia, center of mass and thrust magnitude do not change between two small thruster events close in time

Thrust Estimation Algorithm

$$I_{s/c}\Delta\vec{\omega} + \Delta\vec{H}_{RWA} + \int_{t_1}^{t_2} \vec{\omega} \times (I_{s/c}\vec{\omega} + \vec{H}_{RWA})dt = \int_{t_1}^{t_2} \vec{\tau}_{net}dt$$

Reaction wheel momentum

$$^{B}\vec{H}_{RWA} = {}^{B}C^{W} \,.\, {}^{W}J \,.\, {}^{W}\vec{\Omega}$$

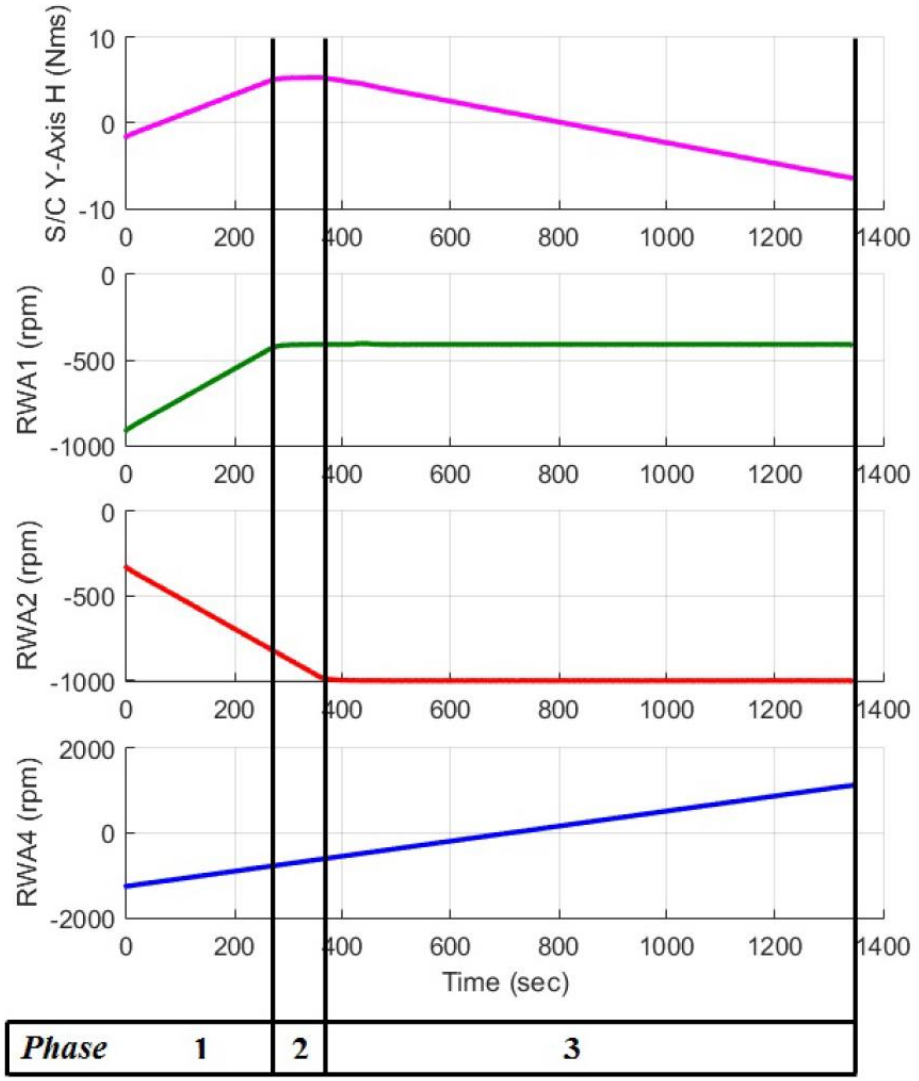
$$\begin{bmatrix} 0 & -1/\sqrt{2} & 1/\sqrt{2} \\ \sqrt{2/3} & -1/\sqrt{6} & -1/\sqrt{6} \\ 1/\sqrt{3} & 1/\sqrt{3} & 1/\sqrt{3} \end{bmatrix}$$

Reaction wheel rates (rad/s)

$$\dot{\vec{H}}_{RWA} \longrightarrow \Delta\vec{H}_{RWA} \neq \vec{H}_{end} - \vec{H}_{start}$$

Equality holds only when $\dot{\vec{H}}$ is constant – for most biases, it is a piecewise linear function

Thrust Estimation Algorithm



- Each RWA changes at the same constant rate, but the desired Δrpm is different for each wheel – so they reach the final speed at different times (called phases)
- Note that Y-axis spacecraft momentum rate of change switches signs at the end of phase 2
- SOLUTION: disregard phase 3

Thrust Estimation Algorithm

$$I_{s/c}\Delta\vec{\omega} + \Delta\vec{H}_{RWA} + \int_{t_1}^{t_2} \vec{\omega} \times (I_{s/c}\vec{\omega} + \vec{H}_{RWA})dt = \int_{t_1}^{t_2} \vec{\tau}_{net}dt$$

Applied external torque:

- ~~Solar pressure~~
- ~~Gravity~~
- ~~Atmosphere~~
- ~~Other negligible sources~~
- Thrusters

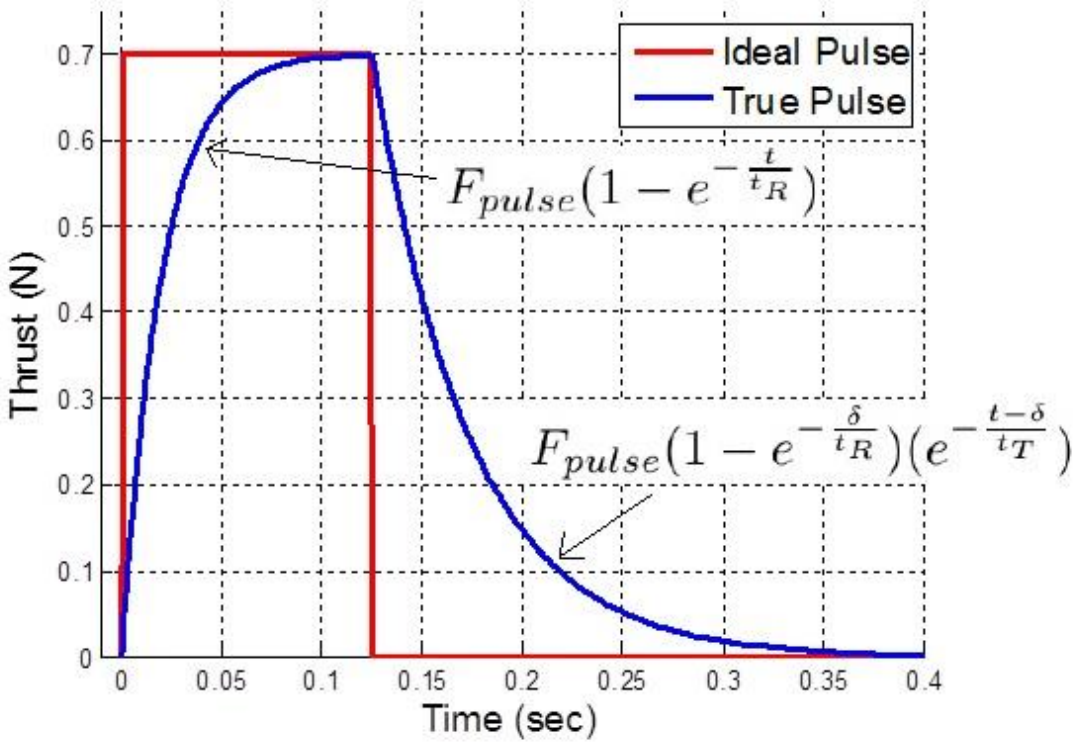
Sum of each thruster's thrust vector

$$\vec{\tau}_{net} = \sum_{i=0}^{8} \vec{\tau}_i$$

Cross product moment arm and force vector

$$\sum_{i=0}^{8} \{\vec{r}_i \times \vec{u}_i \int_{t_1}^{t_2} F_i dt\}$$

Thrust Estimation Algorithm



$$\int_{t_1}^{t_2} F_i dt = N_i \int_{pulse} F_i dt = N_i F_i[\delta + (t_T - t_R)(1 - e^{-\frac{\delta}{t_R}})] = F_i \Delta s_i$$

Tail-off time updated four times

Rise time assumed constant throughout the mission

Thrust Estimation Algorithm

$$I_{s/c}\Delta\vec{\omega} + \Delta\vec{H}_{RWA} + \int_{t_1}^{t_2} \vec{\omega} \times (I_{s/c}\vec{\omega} + \vec{H}_{RWA})dt = \int_{t_1}^{t_2} \vec{\tau}_{net}dt$$

$$\begin{bmatrix} \Delta H_{total,x} \\ \Delta H_{total,y} \end{bmatrix} = \begin{bmatrix} Q_{xy,(2x4)} \end{bmatrix} \begin{bmatrix} F_{Z1} \\ F_{Z2} \\ F_{Z3} \\ F_{Z4} \end{bmatrix}$$

$$\begin{bmatrix} \Delta H_{total,z} \end{bmatrix} = \begin{bmatrix} Q_{z,(1x2)} \end{bmatrix} \begin{bmatrix} F_{Y1/3} \\ F_{Y2/4} \end{bmatrix}$$

Q contains moment arm and on-time information

Note the size of the Q's!
More unknowns than equations

Previous solution – solve equation many times during a bias, solve system using pseudoinverse

Current solution – pair two adjacent events to obtain a fully determined system

Thrust Estimation Algorithm

$$\begin{bmatrix} (\Delta H_{total,z})|_\alpha \\ (\Delta H_{total,z})|_\beta \end{bmatrix} = \begin{bmatrix} (Q_{z,(1x2)})|_\alpha \\ (Q_{z,(1x2)})|_\beta \end{bmatrix} \begin{bmatrix} F_{Y1/3} \\ F_{Y2/4} \end{bmatrix}$$

$$\begin{bmatrix} (\Delta H_{total,x})|_\alpha \\ (\Delta H_{total,y})|_\alpha \\ (\Delta H_{total,x})|_\beta \\ (\Delta H_{total,y})|_\beta \end{bmatrix} = \begin{bmatrix} (Q_{xy,(2x4)})|_\alpha \\ (Q_{xy,(2x4)})|_\beta \end{bmatrix} \begin{bmatrix} F_{Z1} \\ F_{Z2} \\ F_{Z3} \\ F_{Z4} \end{bmatrix}$$

Spacecraft Telemetry

- S/C body rates (rad/s)
- RWA rates (rpm)
- Individual thruster on-time

"Known" Parameters

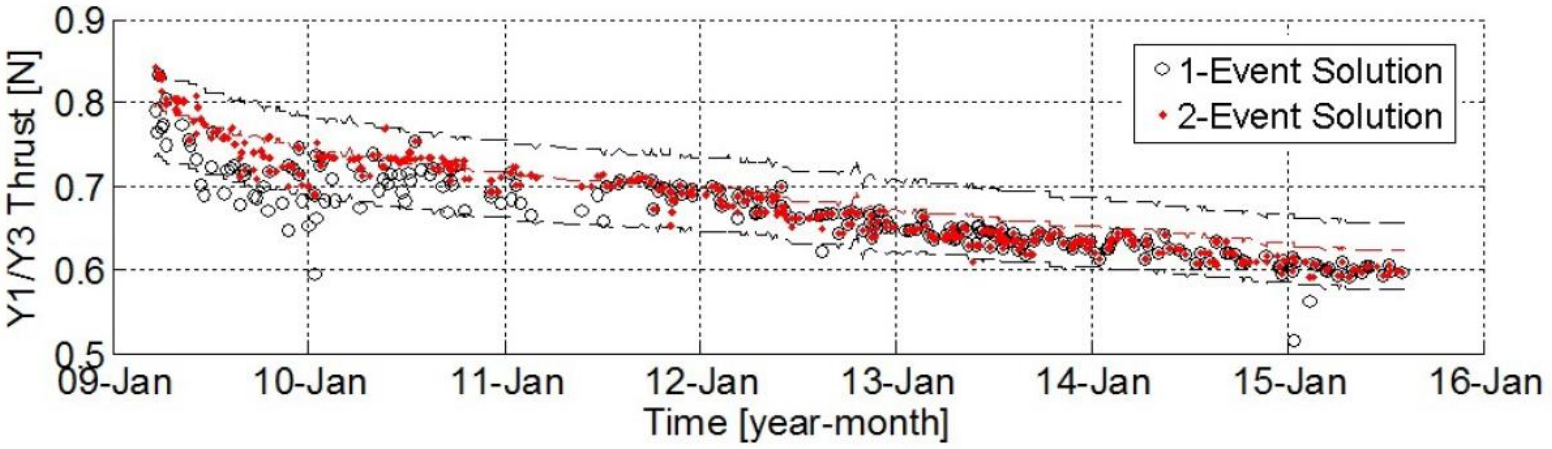
- Products of inertia
- Rise, tail-off times

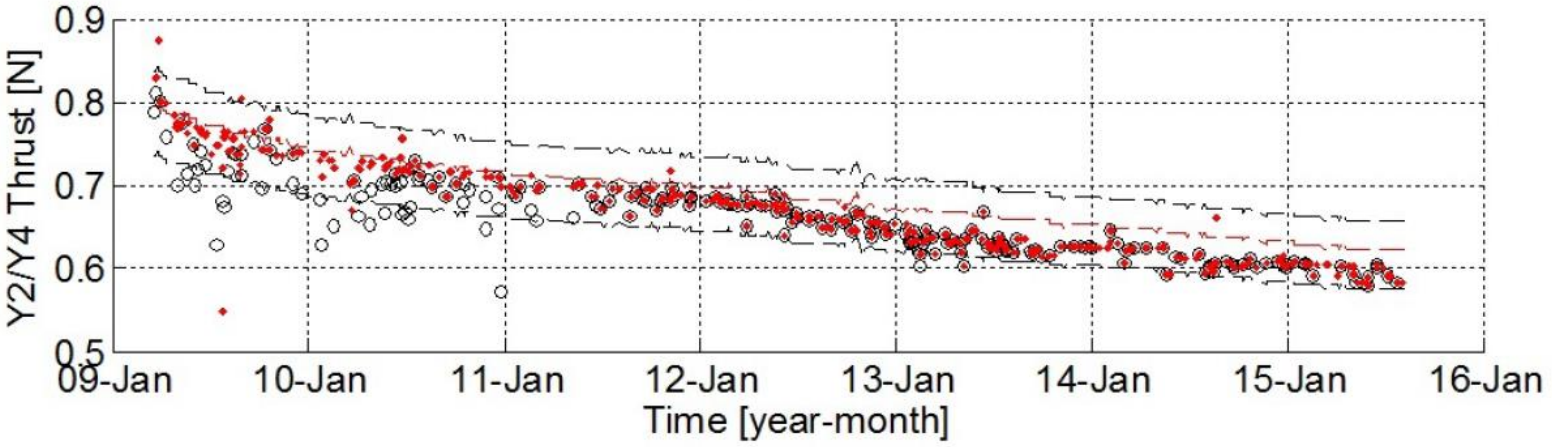
Algorithm

Individual Thrust Magnitude Estimates

Results: Verification

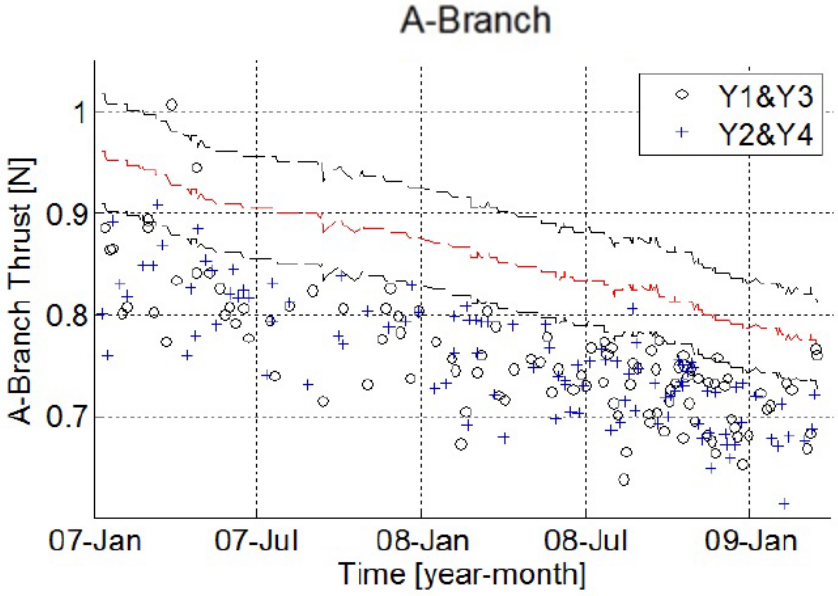
- For any biasing event in which only one of the Y-thruster pairs is used, that equation becomes fully determined
- Calculate both independently and paired for comparison

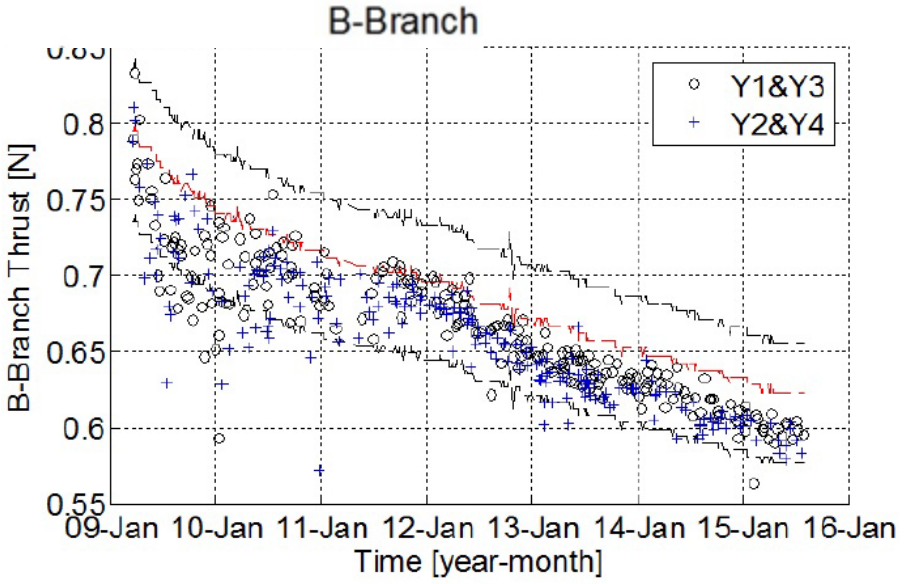




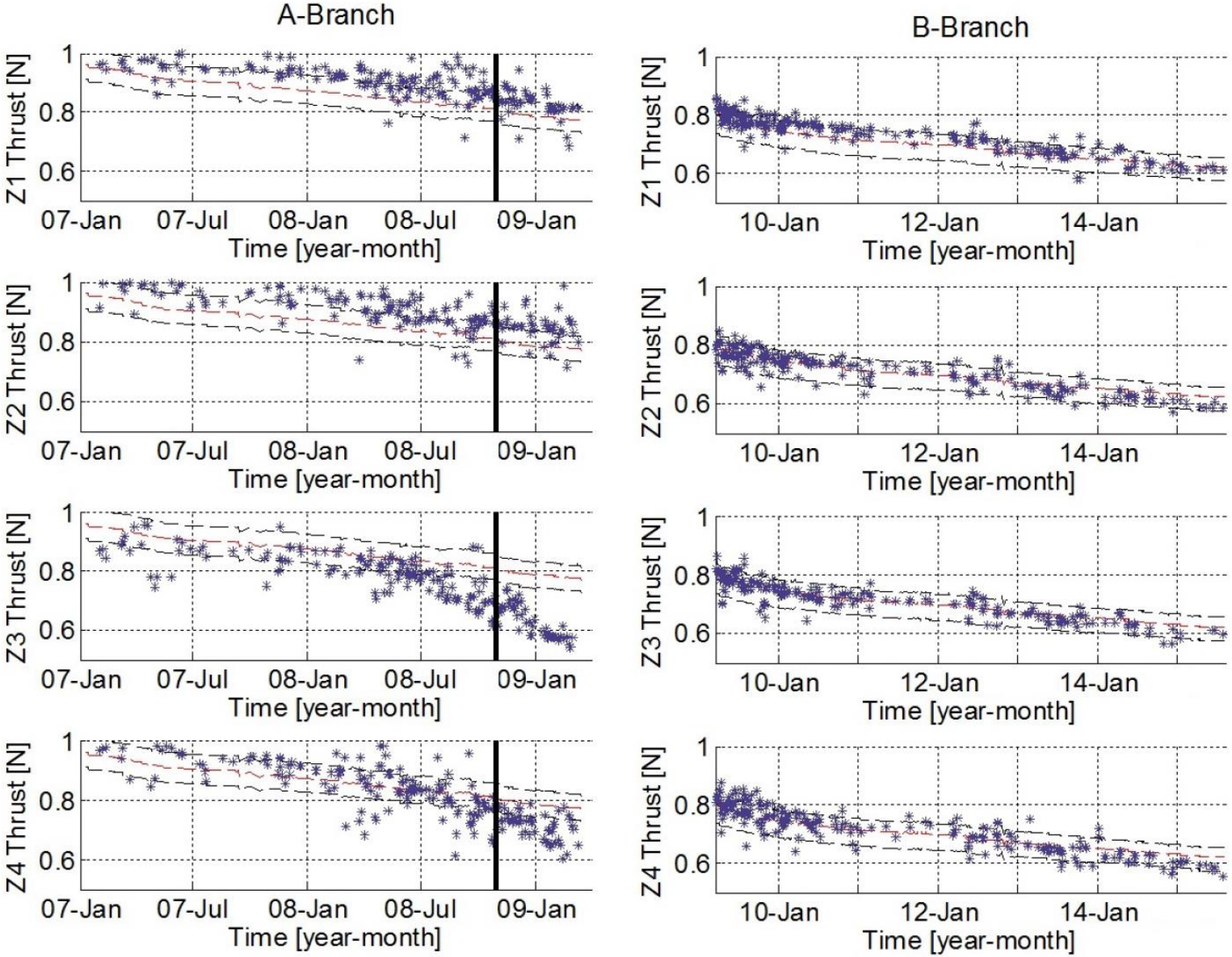
Results: Y-Thrusters

- Thrust is a function of tank pressure, so there is a certain amount of expected degradation
- Hardware degradation would result in a departure from the expected thrust level
- Y-thruster results for A-branch follow the expected trend, but show a constant offset from the predicted thrust
  - Algorithm is sensitive to rise and tail-off time, and a discrepancy between the used and true values would manifest as a constant offset





Results: Z-Thrusters



Conclusions

- Noise in the thrust estimates results from noise in the telemetry
- Algorithm produces accurate thrust estimates for trending analysis
- Y-thrusters on both A-branch and B-branch are in good health
- A-branch Z3 and Z4 thrusters are significantly degraded
- B-branch Z-thrusters are in good health
  - Z4 has been consistently on the low end of the expected thrust envelope, but has been following the expected trend
- This trending analysis, when coupled with other independent detection methods, should identify performance problems early enough for mitigation strategies to be explored