A Flight-Calibrated Methodology for Determination of Cassini Thruster On-Times for Reaction Wheel Biases

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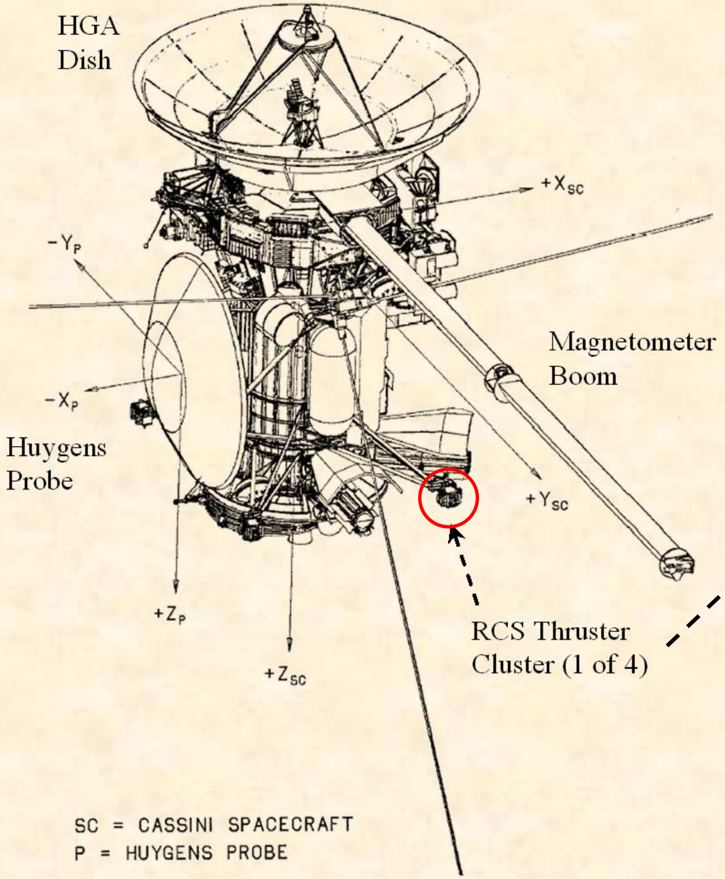
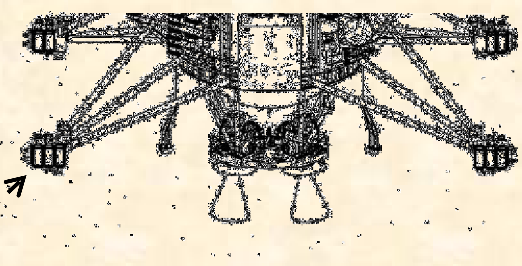
Overview

- The Cassini spacecraft, the largest and most complex interplanetary spacecraft ever built, continues to undertake unique scientific observations of planet Saturn, Titan, Enceladus, and other moons of the ring world
- In order to maintain a stable attitude during the course of its mission, this three-axis stabilized spacecraft uses two different control systems: the Reaction Control System (or RCS) and the Reaction Wheel Assembly (RWA) control system
- In the course of its mission, Cassini performs numerous reaction wheel momentum biases (or unloads) using its reaction control thrusters
- The use of the RCS thrusters often imparts undesired velocity changes (ΔVs) on the spacecraft and it is crucial for Cassini navigation and attitude control teams to be able to, quickly but accurately, predict the hydrazine usage and ΔV vector in Earth Mean Equatorial (J2000) inertial coordinates for reaction wheel bias events, without actually having to spend time and resources simulating the event in a dynamic or hardware-in-the-loop simulation environments
- The flight-calibrated methodology described in this paper, and the ground software developed thereof, are designed to provide the RCS thruster on-times, with acceptable accuracy and without any form of dynamic simulation, for reaction wheel biases, along with the hydrazine usage and the ΔV in EME-2000 inertial frame

Introduction

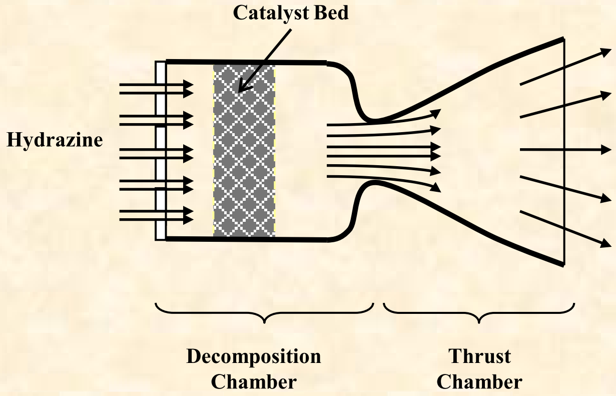
- Completing its 4-year prime mission, and just about ending its 2-year Equinox extended mission, the Cassini spacecraft successfully carries on its observation of Saturn and continues to be in excellent health in the harsh environment of space at a distance of ~9.5 AU
- The Attitude and Articulation Control Subsystem (AACS) of Cassini is responsible for estimation and control of the spacecraft attitude (using RCS and RWA control systems) and execution of ground-commanded spacecraft ΔVs

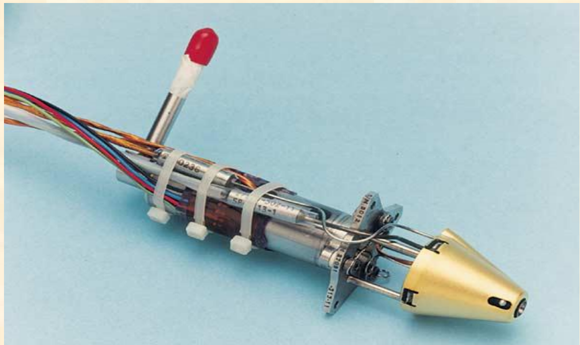




Monopropellant Hydrazine Propulsion System

- The Propulsion Module Subsystem (PMS) of Cassini consists of monopropellant and bipropellant systems
  - The “biprop” is used for spacecraft’s orbital maneuvers and trajectory corrections
  - The “monoprop” is the blow-down type and consists of a single hydrazine tank, a helium recharge tank, and 16 (8 primary or A-Branch and 8 backup or B-Branch) attitude control thrusters with thrust range of 0.5-1 N
- Hydrazine monoprop system generates thrust by ejecting high velocity gases through chemical decomposition of hydrazine by a catalyst bed (cat-bed)
  - The cat-bed is made of platinum/iridium on an aluminum substrate with electric heaters on the surface
  - Heaters improve the chemical reaction transients and prevent damage to the cat-bed
  - Hydrazine decomposes into ammonia exothermically, and the NH_3 in turn decomposes into H_2 and N_2 endothermically (adiabatic flame temperature is in the 1200 C range)
- Attitude control applications of monoprop hydrazine engines require operation over wide ranges of duty cycles and pulse widths and for such uses, the pulsing specific impulse and minimum impulse bit (Ibit) are both very important

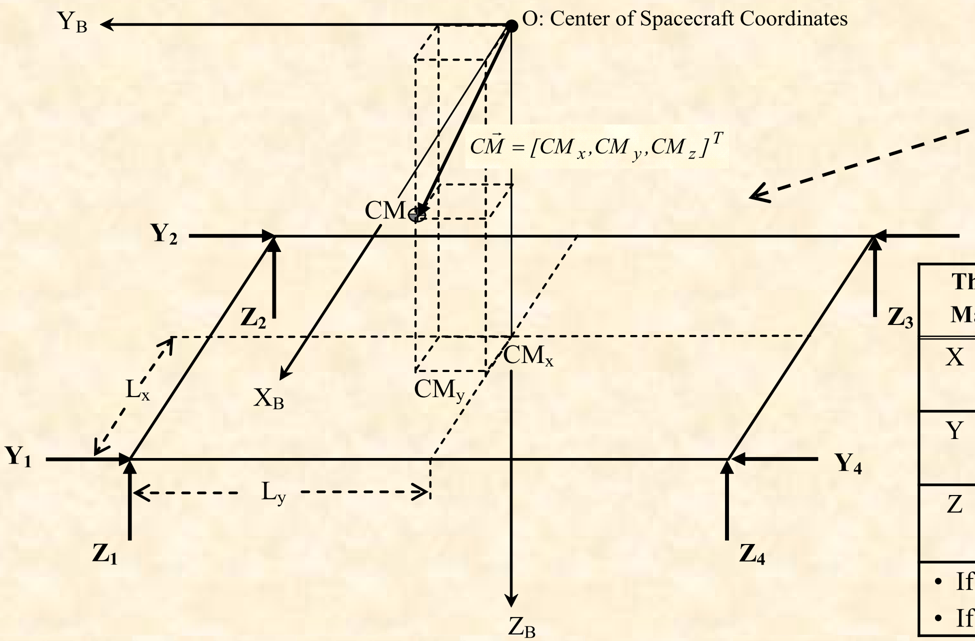




Courtesy Aerojet, a GenCorp Inc.

Cassini Reaction Control System

- Cassini RCS is responsible for maintaining the three-axis attitude control for the spacecraft, when the reaction wheels are not operating, and perform many other unique functions one of which is management of the momentum of RWA
- For pointing control about +Z axis, Y_2 and Y_4 thrusters fire simultaneously, and for pointing control about –Z axis, Y_1 and Y_3 thrusters fire simultaneously
  - Thrusts generated by these firings will almost cancel each other, and the ΔV imparted on the spacecraft will be negligible
- On the other hand, for pointing controls about the spacecraft's X and Y axes will involve firings of the Z-facing thrusters
  - Since these Z-facing thrusters all point in the same direction, their firing generates unwanted ΔV on the spacecraft that must be predicted



The X-axis control authority with B-branch thrusters is ~4% larger than that generated by A-branch thrusters, while the Y-axis and Z-axis control authorities are identical

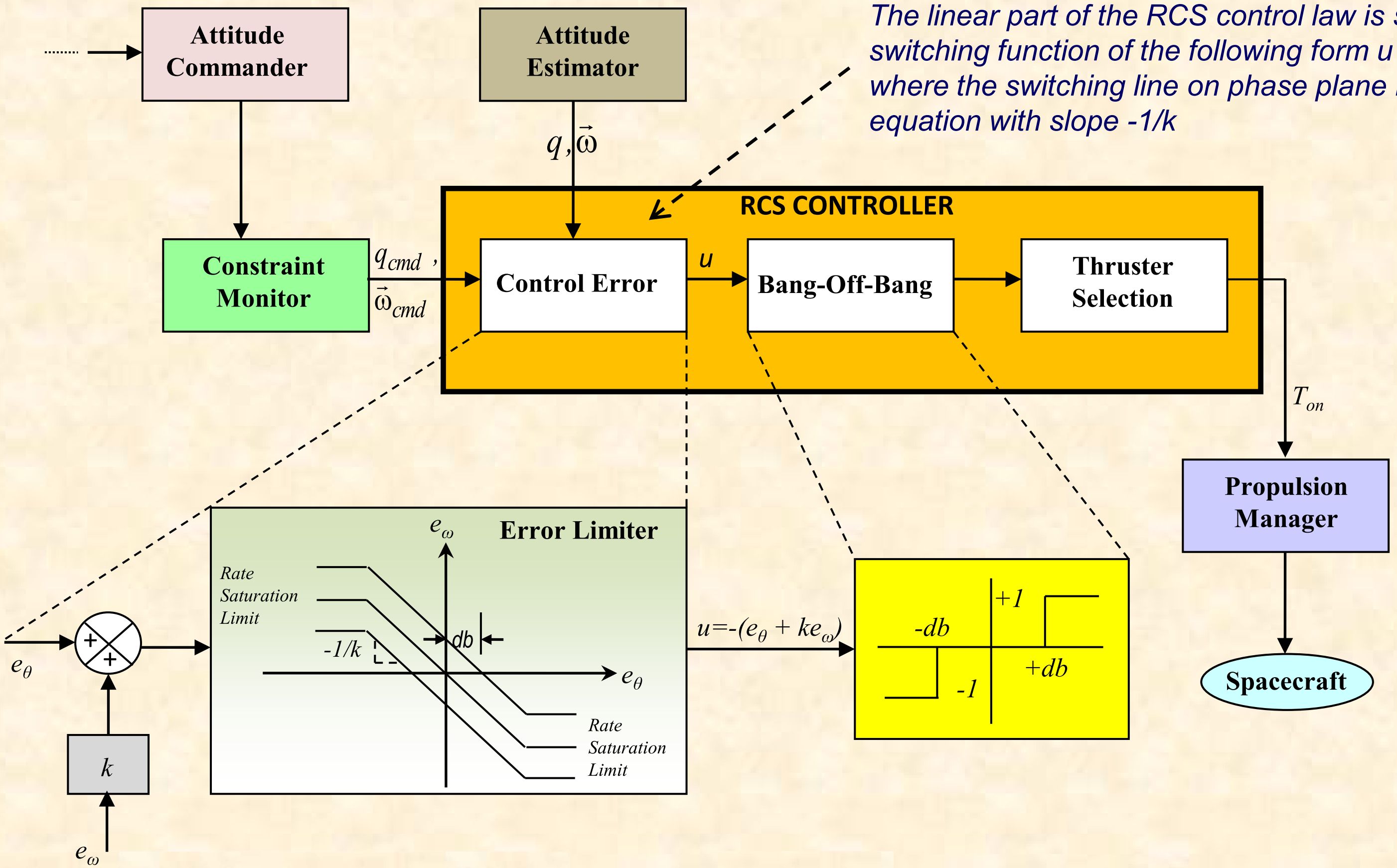
Thruster Mapping		Z-Facing Thrusters Z_1	Z-Facing Thrusters Z_2	Z-Facing Thrusters Z_3	Z-Facing Thrusters Z_4	Y-Facing Thrusters Y_1	Y-Facing Thrusters Y_2	Y-Facing Thrusters Y_3	Y-Facing Thrusters Y_4
X	+			×	×				
	-	×	×						
Y	+	×			×				
	-		×	×					
Z	+						×		×
	-					×		×	

- If Z_1 and Z_3 are both on, then Z_1 and Z_3 firings are inhibited
- If Z_2 and Z_4 are both on, then Z_2 are Z_4 firings are inhibited

Bang-Off-Bang RCS Controller

- The RCS controller consists of a classical bang-off-bang controller, a dead-band, and a set of thruster mapping logic, and it takes both position and rate error signals and processes them through these three components
  - The error signals, which are the weighted sums of per-axis attitude and rate errors, are used to control thruster firings
  - The RCS controller stabilizes the spacecraft's inertial attitude dynamics by feeding back the current spacecraft attitude profiles (position and rate) using the on-board Stellar Reference Unit (SRU) and/or the 3-axis Inertial Reference Unit (IRU), while incorporating an adaptive feature to produce one-sided limit cycles in the presence of small environmental torque

The linear part of the RCS control law is simply a switching function of the following form $u = -(e_\theta + k e_\omega)$, where the switching line on phase plane is a linear equation with slope -1/k



RCS Thruster Pulse Model

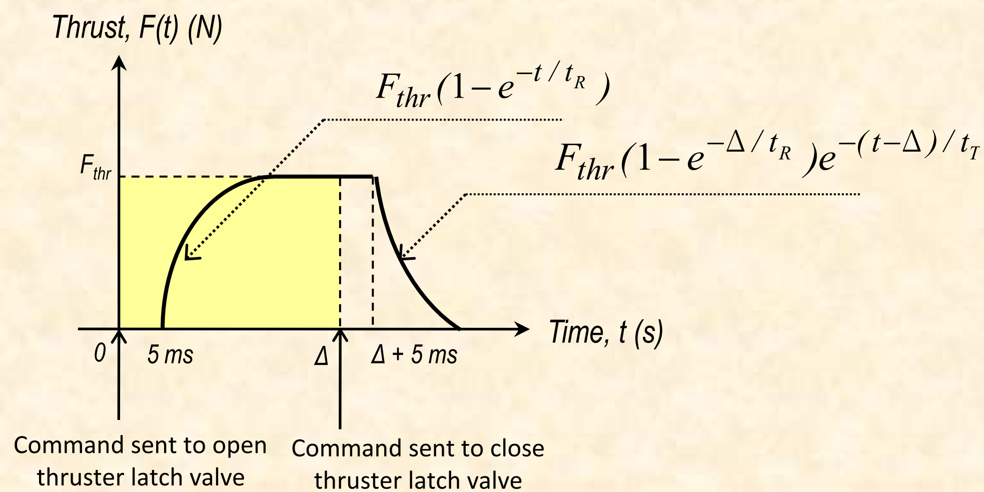
- Each RCS thruster pulse is modeled according to figure below
  - The four parameters F_{thr}, Δ, t_R, and t_T are the steady-state thrust, the commanded pulse width, the exponential rise-time constant, and the exponential tail-off time constant, respectively
- The residual impulse (I_{res}) for a single thruster pulse of width *Δ* equals:

$$I_{res}(\Delta) = \int_0^{\Delta} F_{thr}(1 - e^{-t/t_R})dt + \int_{\Delta}^{\infty} F_{thr}(1 - e^{-\Delta/t_R})e^{-(t-\Delta)/t_T}dt - F_{thr}\Delta$$

$$= F_{thr}(t_T - t_R)(1 - e^{-\Delta/t_R}) \approx F_{thr}(t_T - t_R)$$

- The commanded impulse associated with a single thruster pulse with pulse width of *Δ*, or the impulse generated by an "ideal" thruster with zero rise and tail-off time constants, is $F_{thr}\Delta$ and is represented by the shaded area
  - The solid thick line indicates the actual pulse

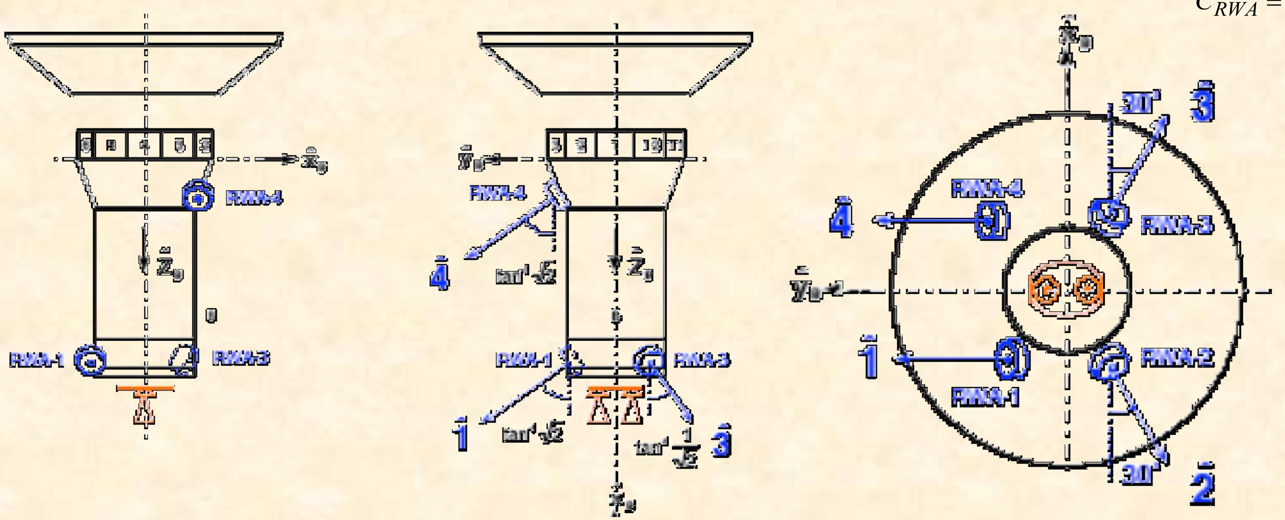
- ➢ The residual impulse is simply the difference between the area under the curve of the actual pulse and that of the ideal pulse
- ➢ During the RWA bias event, the RCS thruster pulses are typically 125 or 250 ms wide
- ➢ For thruster pulse width of 125 ms (or 250 ms), $I_{res}(\Delta) \approx F_{thr}(t_T - t_R)$ is a sufficiently good assumption



Cassini Reaction Wheel Assembly

- Cassini has a set of three fixed reaction wheels that are oriented such that their spin axes make equal angles with the spacecraft's Z-axis
  - Each wheel is considered a Reaction Wheel Assembly (RWA), and the three fixed reaction wheels are named RWA 1, 2, and 3, respectively
  - In addition, Cassini has a backup, articulatable reaction wheel (RWA 4)
  - Currently, RWA 3 is out of commission and the spin axis of RWA 4 is co-aligned with RWA 3
- The reaction wheel control system is a proportional-plus-derivative controller
  - This control system determines the desired torque on the spacecraft, and this torque vector is projected along each wheel axis to determine the contribution of each wheel
  - The result is then negated to determine the commanded torque on each wheel
  - The torque of the wheel on the spacecraft is equal and opposite to the RWA torque
- The 3-axis angular momentum vector in RWA frame is transformed to the spacecraft's fixed frame via the transformation matrix given below

$$C_{RWA}^{SC} = \begin{pmatrix} 0 & -\frac{1}{\sqrt{2}} & 0.713318 \\ \sqrt{\frac{2}{3}} & -\frac{1}{\sqrt{6}} & -0.402252 \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & 0.573909 \end{pmatrix}$$

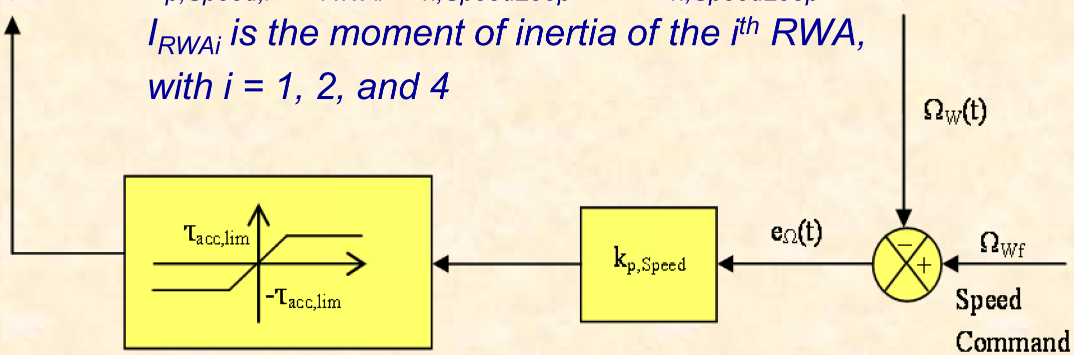


RWA Hardware Manager – The Speed Loop

- The RWA manager is an algorithm that accepts spacecraft torque requests from attitude control algorithms and attempts to satisfy those requests by commanding the appropriate wheel torques
  - It provides wheel momentum estimates to the attitude estimator algorithms and also is capable of enforcing speed control commands for each wheel used mainly to dump excess momentum that has accumulated in the wheels
- The RWA hardware manager operates in three possible modes: the torque mode, the speed control mode, and the coast mode
  - The function implemented by the RWA manager in speed control mode is individual wheel speed control, and the simplified block diagram for the speed loop is shown below
  - A 0.01 Hz bandwidth (= $f_{n,SpeedLoop}$) proportional-integral control loop within the RWA manager causes the wheel speed to track the ideal speed and thus the ideal speed will reflect the current value of wheel speed
  - The value of ideal speed is compared to speed command to form a rate error signal
  - The rate error is multiplied by the gain $k_{p,Speed,i}$ to form a torque command, with i = 1, 2, and 4 for the three prime RWAs (RWA-1, 2, and 4), respectively

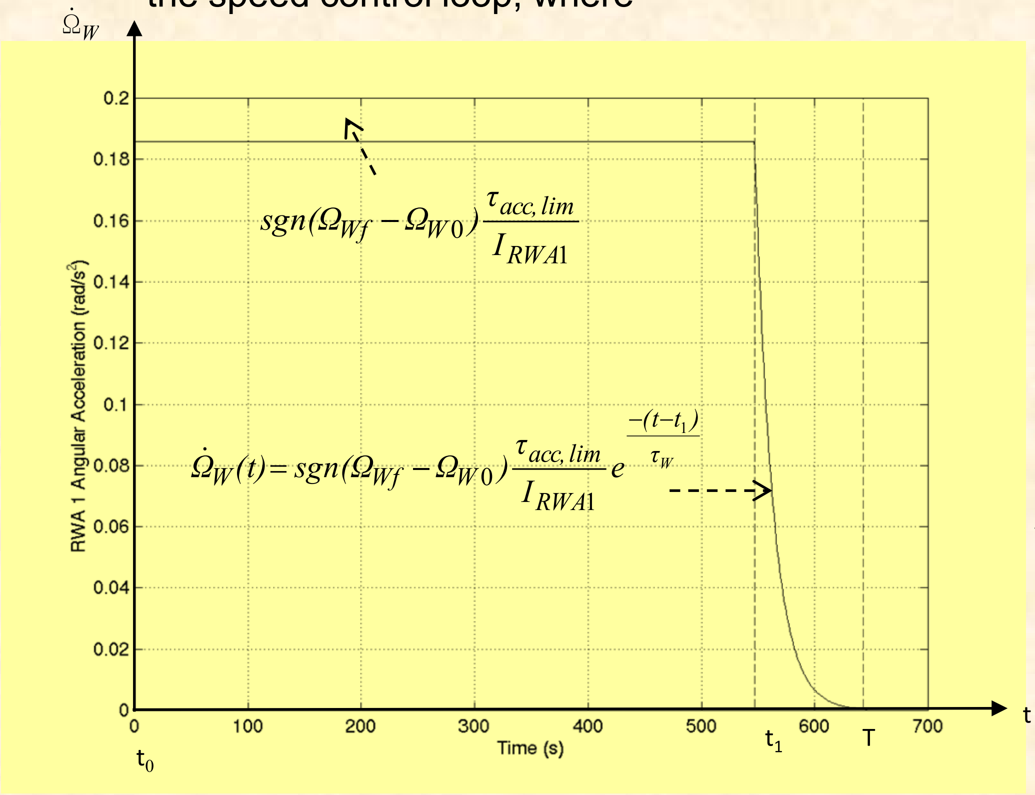
$k_{p,Speed,i} = I_{RWAi}\,\omega_{n,SpeedLoop} = 2\pi f_{n,SpeedLoop}$

I_{RWAi} is the moment of inertia of the i^{th} RWA, with i = 1, 2, and 4



RWA Angular Acceleration Profile for a Bias Event

- The bias assumed for figure below and the next figure is changing the RWA-1 rate from 0 to +1000 RPM
  - Parameters t_0 and T are the start and end times of bias for an RWA (RWA-1 in this case)
  - The time t_1 marks the end of the linear range of the RWA rate profile
  - The rates Ω_W, Ω_{W0}, and Ω_{W1} are the RWA rate at times t, t_0, and t_1, respectively
  - The rate Ω_{Wf} is approximately the RWA rate at time T
  - The parameter $\dot{\Omega}_W$ is the RWA acceleration and τ_W is the time constant associated with the speed control loop, where



$$\tau_W = \frac{1}{\omega_{n,SpeedLoop}} = \frac{I_{RWAi}}{k_{p,Speed,i}}$$

Throughout the linear ramp region of the profiles, when $t_0 \le t \le t_1$:

$$\dot{\Omega}_W(t) = sgn(\Omega_{Wf} - \Omega_{W0})\frac{\tau_{acc,lim}}{I_{RWAi}}$$

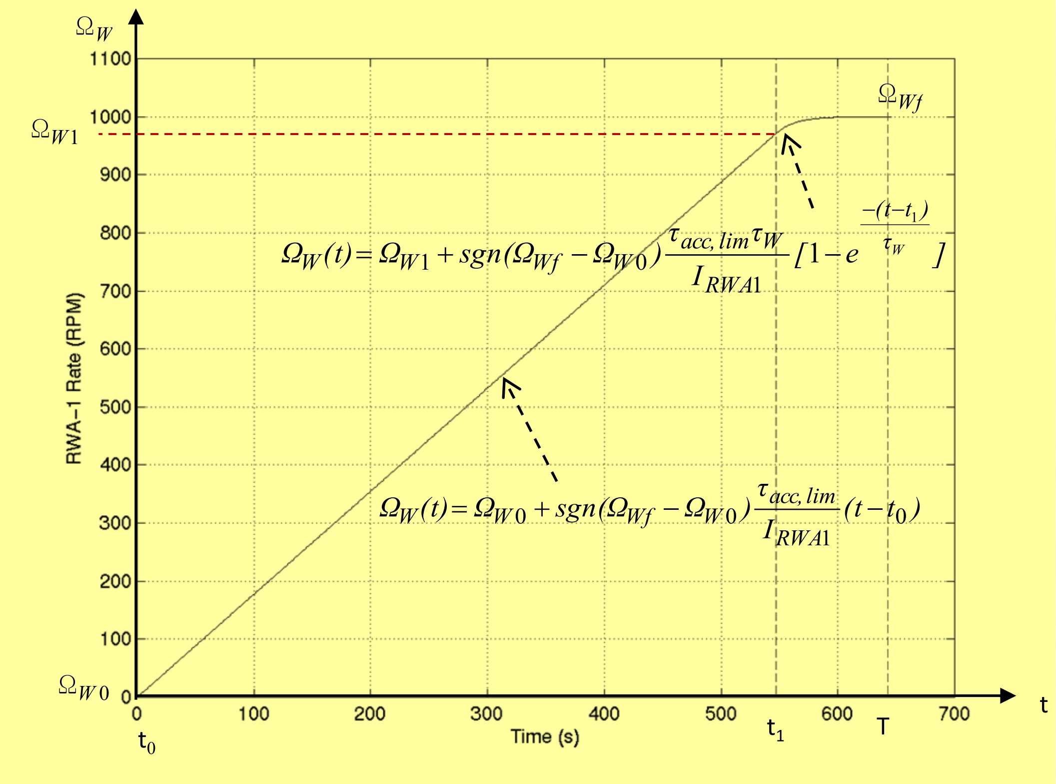
$$\Omega_W(t) = \Omega_{W0} + sgn(\Omega_{Wf} - \Omega_{W0})\frac{\tau_{acc,lim}}{I_{RWAi}}(t - t_0)$$

RWA Angular Rate Profile for the Same Bias Event

- Once the RWA rate gets close the commanded rate, the speed control loop enters its linear range and the RWA rate and acceleration take the characteristic of exponentials, and in the linear range of the speed control loop

Therefore, throughout the exponential region of the profiles, when $t_1 \leq t \leq T$:

$$\dot{\Omega}_W(t) = sgn(\Omega_{Wf} - \Omega_{W0}) \frac{\tau_{acc,lim}}{I_{RWAi}} e^{\frac{-(t-t_1)}{\tau_W}} \quad \text{and} \quad \Omega_W(t) = \Omega_{W1} + sgn(\Omega_{Wf} - \Omega_{W0}) \frac{\tau_{acc,lim}\tau_W}{I_{RWAi}} [1 - e^{\frac{-(t-t_1)}{\tau_W}}]$$



At the boundary of the linear range of speed control loop, i.e. at $t = t_1$:

$$t_1 = t_0 + sgn(\Omega_{Wf} - \Omega_{W0}) \frac{I_{RWAi}}{\tau_{acc,lim}} (\Omega_{Wf} - \Omega_{W0}) - \tau_W$$

In order to determine the time T for i[th] RWA, let $T = t_1 + n\tau_W$ and

$$N = \frac{\Omega_W(T) - \Omega_{W1}}{\Omega_{Wf} - \Omega_{W1}}$$

Now, $N = 1 - e^{-n}$ or $n = -ln(1 - N)$

The parameter N = 99.75% when n = 6, and therefore,

$$T = t_1 + 6\tau_W$$
$$= sgn(\Omega_{Wf} - \Omega_{W0}) \frac{I_{RWAi}}{\tau_{acc,lim}} (\Omega_{Wf} - \Omega_{W0})$$
$$+ t_0 + 5\tau_W$$

Thruster On-Time Determination for Ideal Thrusters

- The RWA biases are always performed under RCS control and while the spacecraft is typically Earth-pointed with a good star coverage for star trackers, i.e. spacecraft's +X pointing along the Z-axis of the EME-2000 inertial frame
  - The attitude dead-band is typically 2 mrad along all three axes throughout the bias event
  - RCS thrusters are fired to maintain the spacecraft's attitude in the presence of RWA dc motor torques and the RWA manager enforces RWA speed control to bias the wheels
  - The Bang-off-Bang RCS controller maintains the spacecraft pointing while RWA rates change from their initial rates to their final commanded rates
- The Euler equation of rotational dynamics for a spacecraft with reaction wheels is given by:

$$I\dot{\vec{\omega}} + \vec{\omega}\times(I\vec{\omega} + \vec{H}_{RWA}) = \vec{\tau}_{Dist} + \vec{\tau}_{Control} - \dot{\vec{H}}_{RWA}$$

- Assuming the RCS control and negligible disturbance torques, $\frac{d}{dt}(I\vec{\omega} + \vec{H}_{RWA}) + \vec{\omega}\times(I\vec{\omega} + \vec{H}_{RWA}) = \vec{\tau}_{RCS}$ where $\vec{\tau}_{RCS}$ is the torque generated by RCS thrusters
- Integrating the above equation and defining *S(ω)* as $S(\vec{\omega}) = \begin{pmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{pmatrix}$ yields:

$$\int_{t_0}^{T} \frac{d}{dt}(I\vec{\omega} + \vec{H}_{RWA})dt + \int_{t_0}^{T} S(\vec{\omega})(I\vec{\omega} + \vec{H}_{RWA})dt = \int_{t_0}^{T} \vec{\tau}_{RCS}dt$$

$$\int_{t_0}^{T} \vec{\tau}_{RCS}dt = \sum_i \vec{L}_{arm,i} \times \vec{F}_{thr,i}[T_{on,i}(T) - T_{on,i}(t_0) + \frac{I_{res,i}}{|\vec{F}_{thr,i}|}]$$ where *i* = 1, …, 8 for 8 primary thrusters, $i \in \{Z_1, Z_2, Z_3, Z_4, Y_1, Y_2, Y_3, Y_4\}$

$$I[\underbrace{\vec{\omega}(T) - \vec{\omega}(t_0)}_{\approx 0}] + [\vec{H}_{RWA}(T) - \vec{H}_{RWA}(t_0)] + I\int_{t_0}^{T} \underbrace{S(\vec{\omega})\vec{\omega}}_{\approx 0}dt + \int_{t_0}^{T} \underbrace{S(\vec{\omega})}_{\approx 0}\vec{H}_{RWA}dt = \int_{t_0}^{T} \vec{\tau}_{RCS}dt$$

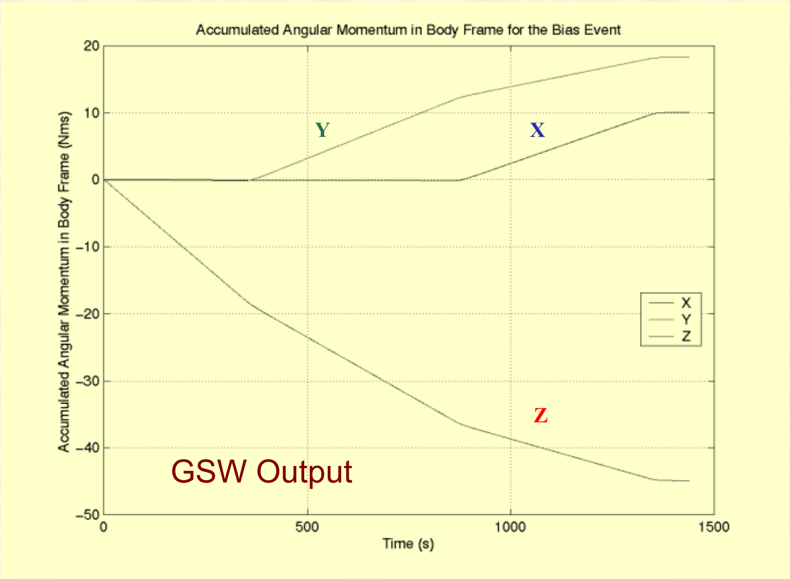
$$\Delta\vec{H} = \vec{H}_{RWA}(T) - \vec{H}_{RWA}(t_0) = \sum_i \vec{L}_{arm,i} \times \vec{F}_{thr,i}[T_{on,i}(T) - T_{on,i}(t_0) + (t_T - t_R)]$$

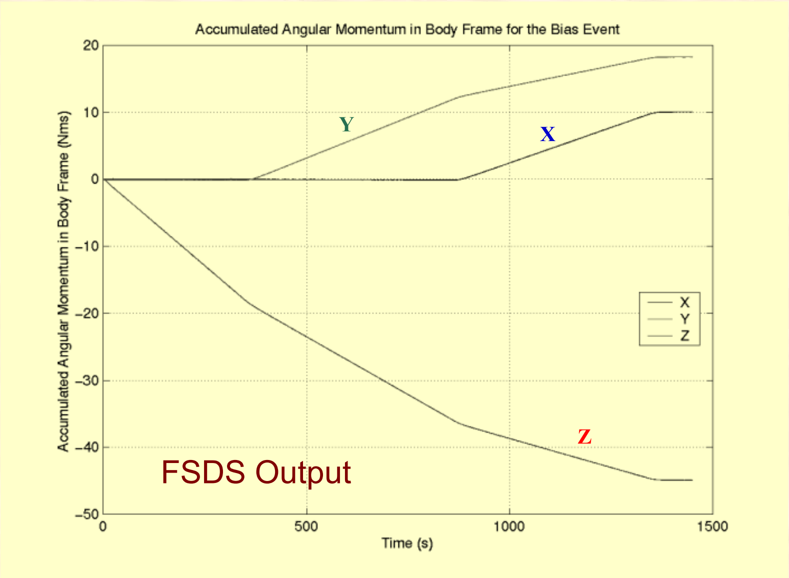
$$\Delta\vec{H} = C_{RWA}^{SC} diag(I_{RWA1}, I_{RWA2}, I_{RWA4})\Delta\vec{\Omega}_{RWA}$$ where $\Delta\vec{\Omega}_{RWA} = \vec{\Omega}_{RWA,f} - \vec{\Omega}_{RWA,i}$

Transformation matrix from RWA frame to spacecraft body frame

On-Time Determination - Continued

- The Cassini AACS team simulates the RWA bias events using a simulation environment called the Flight Software Development System (FSDS)
  - The FSDS is a high-fidelity test-bed that is used to perform guidance, control, and fault protection simulations
  - It is a closed-loop environment using the latest version of the AACS Flight Software
- Figures below depict the three components of $\Delta\vec{H}$ vector output from the ground software (GSW) tool developed using the described methodology, side by side with the FSDS simulation output for the RWA bias event that occurred on February 13, 2010 in which $\vec{\Omega}_{RWA,i} = [+1078, +1146, +1047]^T$ RPM and $\vec{\Omega}_{RWA,f} = [+432, -1293, -508]^T$ RPM
  - This bias event is used as an example throughout this presentation
- As seen in these figures, the GSW output matches closely with the FSDS output

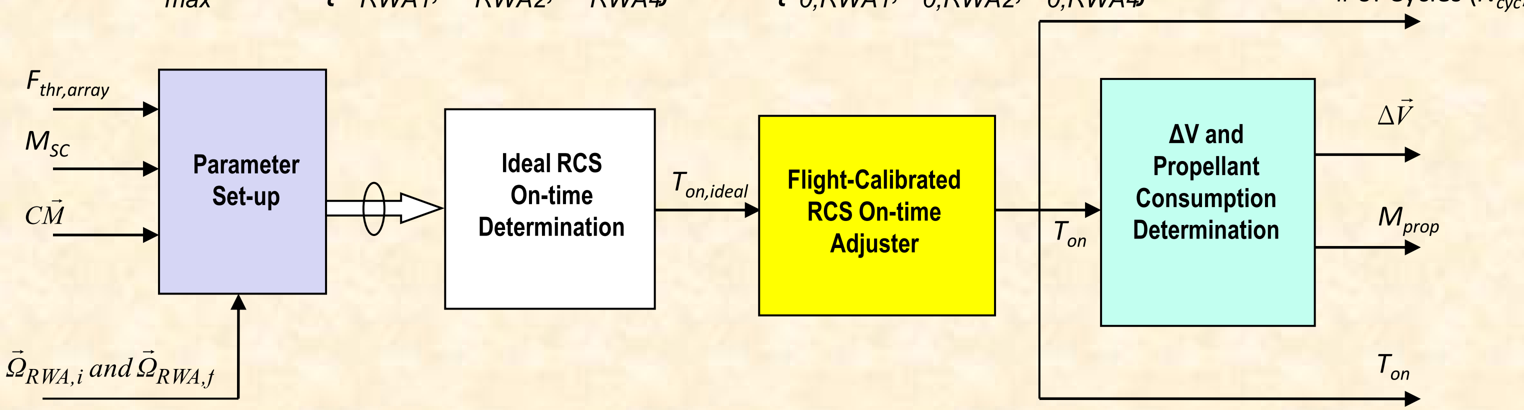




Block Diagram of the Methodology

- Figure below depicts the steps involved in the methodology described in this paper
  - The block titled "Ideal RCS On-time Determination" is the core block
- The inputs consist of the array of thruster magnitudes for eight primary RCS thrusters, $F_{thr,array}$, the spacecraft wet mass, M_{sc}, the spacecraft c.m. location in spacecraft coordinate frame, $\vec{CM}$, and the initial and final RWA rates, $\vec{\Omega}_{RWA,i}$ and $\vec{\Omega}_{RWA,f}$
  - All the programmable and constant parameters used in the entire GSW are set in the block titled "Parameter Set-up"
- After setting up the initial parameters, the angular momentum profile due to RWA rate changes in body frame, $\Delta\vec{H}$, is computed inside the "Ideal RCS On-time Determination" block
- In order to determine this angular momentum, first a set of three time tags for each RWA is determined which includes the time tag for the start of each RWA rate change, $t_{0,RWAi}$, the end time for the linear range of RWA rate change, $t_{1,RWAi}$, and the time tag for the end time of the bias for each RWA, T_{RWAi} with i = 1, 2, and 4
- The difference between the maximum of the three T_{RWAi} time tags and the minimum of the three $t_{0,RWAi}$ time tags is the bias time duration, T_{max}, i.e.

$$T_{max} = max\{T_{RWA1}, T_{RWA2}, T_{RWA4}\} - min\{t_{0,RWA1}, t_{0,RWA2}, t_{0,RWA4}\}$$



Analytical Thruster On-Time Determination Algorithm

- The GSW runs at every s_{sample} sample period, where s_{sample} is reprogrammable and is typically equal to 1 s
  - At every sample period, the vector is input to a module within the Ideal RCS On-time Determination block that computes the RCS on-times during the sample period assuming ideal, rectangular thruster pulses, i.e. the residual impulse effect is ignored and the on-times are determined analytically
- There are altogether 10 different cases and the GSW determines which case applies during each sample period and we will only examine one case here

$$\theta_{Z1} = 180° + Tan^{-1}(-\frac{L_x - CM_x}{L_y - CM_y})$$

$$\theta_{Z3} = Tan^{-1}(-\frac{L_x + CM_x}{L_y + CM_y})$$

$$\theta_{Z4} = Tan^{-1}(\frac{L_x - CM_x}{L_y + CM_y})$$

Representative Case: Let $\Delta\vec{H} = [\Delta H_x, \Delta H_y, 0]^T$ with with $\Delta H_x > 0$ and $\Delta H_y > 0$

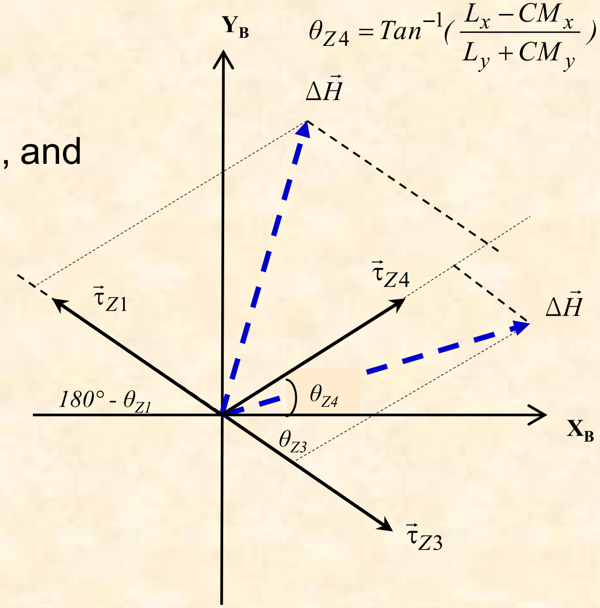
If $\frac{\Delta H_y}{\Delta H_x} = \frac{L_x - CM_x}{L_y + CM_y}$, then $T_{on,Z_1} = T_{on,Z_3} = 0$ [s]

Thrusters: (Z_1, Z_4) or (Z_3, Z_4) with Z_4 exercised the most

If $0 < \frac{\Delta H_y}{\Delta H_x} < \frac{L_x - CM_x}{L_y + CM_y}$, the on-time of Z_3 and Z_4 thrusters, and

if $\frac{\Delta H_y}{\Delta H_x} > \frac{L_x - CM_x}{L_y + CM_y}$, the on-times of Z_1 and Z_4 thrusters

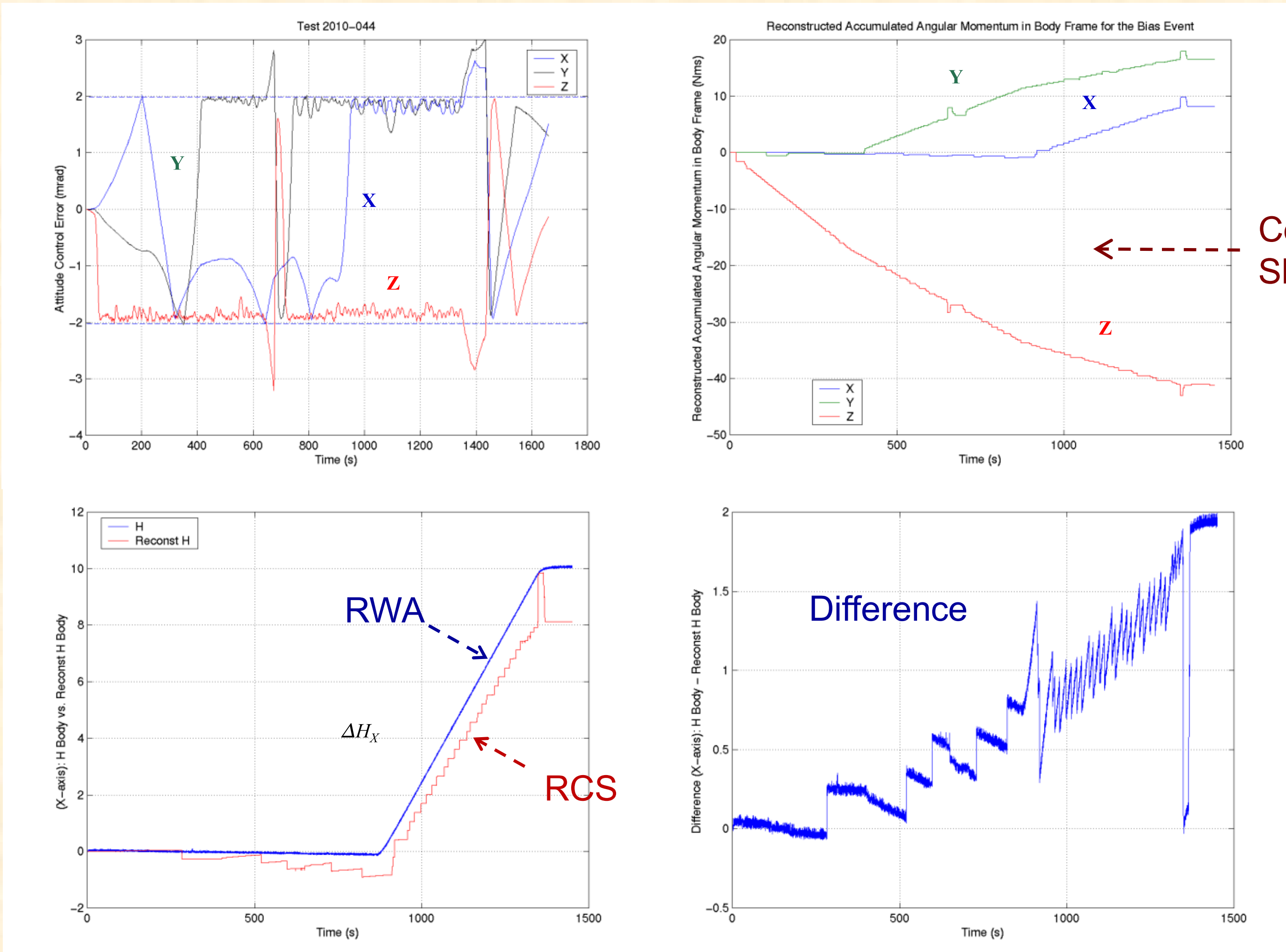
are computed analytically



The total ΔV and the total consumed propellant, M_{prop}, are computed in the last block using the flight-calibrated total thruster on-times

Flight-Calibrated Thruster On-Times

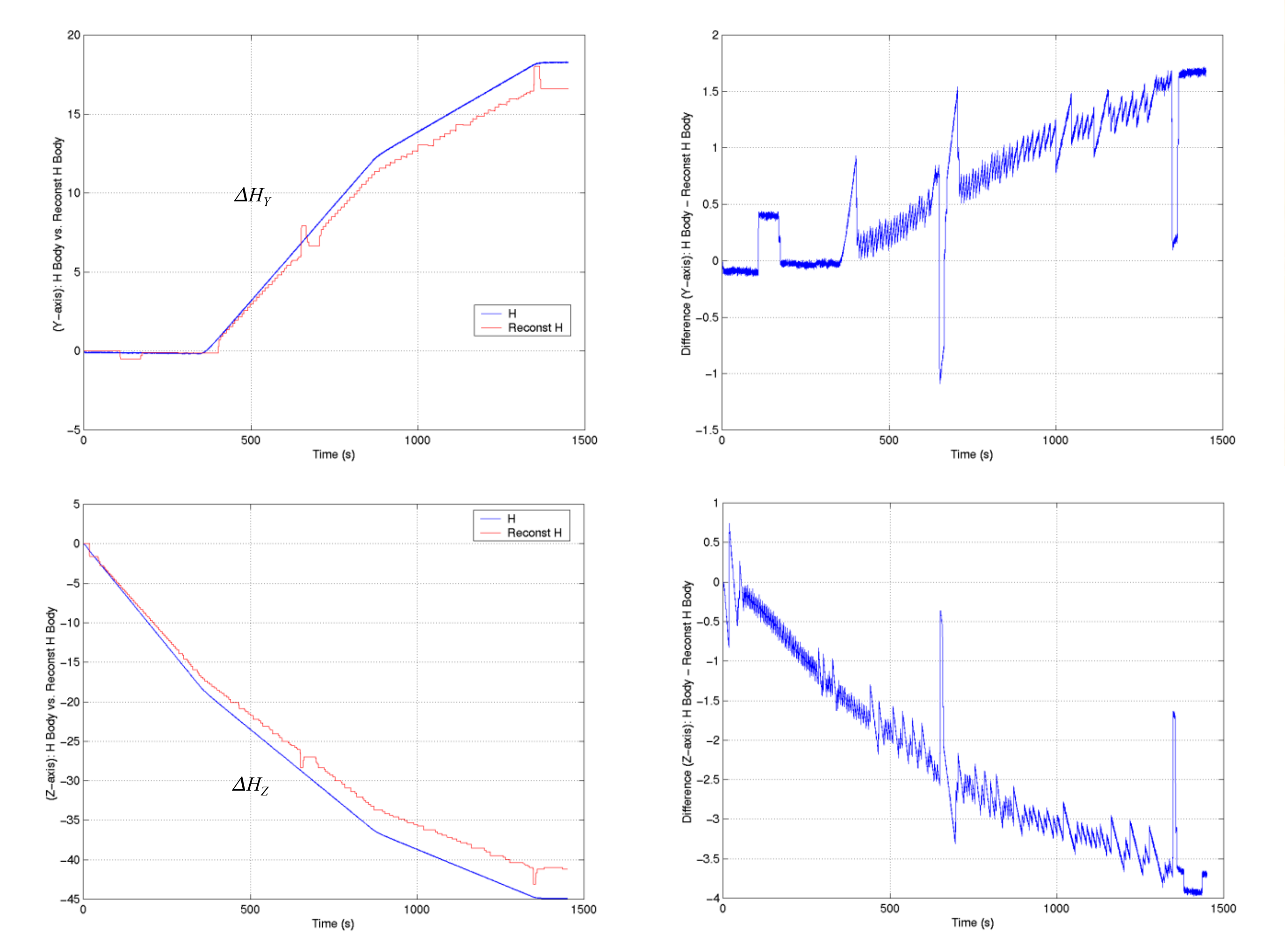
- Because of the RCS controller's characteristics, per-axis angular momentum profile from thruster firings deviates from the respective angular momentum profile from the RWA spin rate changes in spacecraft body frame, and at the end of the bias event, the difference of the two per-axis profiles is a few Nms



Compare to Slide 13

Flight-Calibrated On-Times - Continued

- After examination of these difference profiles from FSDS simulations and flight data of several bias events, these "deltas" are modeled to adjust thruster on-times, and despite many challenges in determining thruster on-times which results from the bang-off-bang RCS thruster controller characteristics, captured below, this methodology generates results that match with flight results with adequate accuracy



Flight-Calibrated RCS On-Time Adjuster

- Inside the “Parameter Set-up” block, a gain array is initialized
  - The entries of this gain array are used for thruster on-time adjustments
- To account for the effect of the residual impulse due to the rise and tail-off time constants of thruster pulses, each ideal thruster on-time, $T_{on,i,ideal}$, is adjusted
  - The thruster on-times of Y-facing thrusters, i.e. Y_1, Y_2, Y_3, and Y_4, are subsequently adjusted by a factor to account for the modeled Z-axis angular momentum deviations
- The thruster on-times of Z-facing thrusters, i.e. Z_1, Z_2, Z_3, and Z_4, are adjusted by a term
- A Boolean flag indicting that the bias is done mainly with Y-facing thrusters, is set to TRUE, when the bias is done mainly with Y-facing thrusters
  - In this case, the Z-facing thruster on-times are small but not zero, and hence, greater adjustments are required
  - If this Boolean flag is FALSE, the angular momentum in body frame at the end of the bias event is first determined and set equal to $\vec{h}$, where $\vec{h} = [h_x, h_y, h_z]^T = \Delta\vec{H}(T_{max})$
- Then, the on-time of Z-facing thrusters are adjusted, using a set of matrix equations, depending on whether $sgn(h_x) \cdot sgn(h_y)$ = -1, +1, or 0
- The number of thruster cycles for each RCS thruster, $N_{cyc,i}$, is also determined from thruster on-times
  - The parameter $N_{cyc,i}$ is then rounded to become a non-negative integer

ΔV and Propellant Consumption

- Total mass of hydrazine used up for the bias event is determined by:

$$M_{prop} = \frac{1}{g_0}\sum_i \frac{F_{thr,i}T_{on,i}}{I_{sp,i}}$$ [kg], where i = 1, …, 8 for 8 primary branch thrusters i.e., $i \in \{Z_1, Z_2, Z_3, Z_4, Y_1, Y_2, Y_3, Y_4\}$

- $I_{sp,i}$ is determined for i^th thruster using the total thruster on-time for i^th thruster, $T_{on,i}$, T_{max}, and a nonlinear empirical formula:

$$T_{max} = max\{T_{RWA1}, T_{RWA2}, T_{RWA4}\} - min\{t_{0,RWA1}, t_{0,RWA2}, t_{0,RWA4}\} \quad \text{[s]}$$

$$I_{sp}(\mu) = P_0 - P_1 e^{-P_2\mu} - P_3 e^{-P_4\mu} \quad \text{[s]} \qquad (\text{for } 0 \le \mu \le \mu_{max,bias})$$

- The ΔV vector in spacecraft body frame is determined by:

$$\Delta\vec{V}^{Body} = \frac{1}{M_{SC}}\sum_j \vec{F}_{thr,j}T_{on,j}$$ [m/s], where i = 1, …, 4 for 4 Z-facing primary branch thrusters, i.e., $j \in \{Z_1, Z_2, Z_3, Z_4\}$

- Since throughout the RWA bias, the attitude is almost fixed in inertial frame, $\Delta\vec{V}^{Body}$ can be transformed to the EME-2000 frame, and

$$\Delta\vec{V}^{EME2000} = C_{Body}^{EME2000} \cdot \Delta\vec{V}^{Body} \quad \text{[m/s]}$$

This matrix is determined from the inertial-to-body quaternion

Comparing Results for 1 (of 8) RWA Bias Events

- The methodology described here is validated using numerous FSDS simulations and the flight data from more than a dozen of RWA biases, with 8 cases given in the paper and 1 case here
  - In general, the FSDS generated thruster on-times and pulses tend to be higher than the respective flight data, and the flight-calibrated on-times generated by the GSW tool are closer to both FSDS and flight compared to the theoretical, unadjusted on-times
- When averaged over the 8 bias cases, the average difference of on-times between the flight data and GSW is ~0.59 s, the average difference in Z-axis ΔV is ~0.79 mm/s, and the average difference in hydrazine mass is ~1.05 grams

RWA Bias Event: 02/13/2010 (DOY 044) Thrust = 0.75 N		GSW (Ideal)	GSW	FSDS Simulation	Flight Data	Abs. Diff. Flight – GSW	%Abs. Diff. (per Flight)
Initial RWA Rates	*RPM*	[+1078, +1146, +1047]				-	-
Final RWA Rates	*RPM*	[+432, -1293, -508]				-	-
Bias Size (RWA Rate Change)	*RPM*	[-646, -2439, -1555]				-	-
Bias Time Duration	*s*	1440				-	-
ΔT_{on} Y_1-Y_3 Thruster Pair	*s*	24.25	23.67	24.14	23.64	0.03	0
ΔT_{on} Y_2-Y_4 Thruster Pair	*s*	0.00	0.00	1.88	1.38	1.38	100
ΔT_{on} Z_1 Thruster	*s*	7.77	11.29	12.94	12.52	1.24	10
ΔT_{on} Z_2 Thruster	*s*	0.07	1.42	2.88	2.50	1.08	43
ΔT_{on} Z_3 Thruster	*s*	0.50	4.53	4.87	5.12	0.59	12
ΔT_{on} Z_4 Thruster	*s*	15.00	15.30	16.59	16.39	1.10	7
Total Z-Facing RCS ΔT_{on}	*s*	23.33	32.53	37.28	36.53	4.00	11
# of Y_1-Y_3 Firing Cycles	-	-	151	160	182	31	17
# of Y_2-Y_4 Firing Cycles	-	-	0	6	7	7	100
# of Z_1 Firing Cycles	-	-	72	91	96	24	25
# of Z_2 Firing Cycles	-	-	9	13	19	10	52
# of Z_3 Firing Cycles	-	-	29	33	42	13	31
# of Z_4 Firing Cycles	-	-	98	113	121	23	19
ΔV_x in Body Frame	*mm/s*	0.00	0.00	0.02	0.02	0.02	100
ΔV_y in Body Frame	*mm/s*	0.00	0.00	-0.02	0.01	0.01	100
ΔV_z in Body Frame	*mm/s*	-7.35	-10.25	-12.61	-12.36	2.10	17
ΔV (Magnitude)	*mm/s*	7.35	10.25	12.61	12.36	2.10	17
Consumed Hydrazine Mass	*grams*	34.4	38.3	38.8	39.0	0.7	2

Ending Remarks

- The use of the RCS thrusters often imparts undesired ΔV on the Cassini spacecraft
- It is crucial for both the Cassini navigation and spacecraft attitude control teams to be able to, quickly but accurately, predict the hydrazine usage *(don't want to run of juice too early!)* and ΔV *(don't want get lost in space!)* in EME-2000 inertial coordinates for reaction wheel bias events, without actually having to spend time and resources simulating the event in FSDS or hardware-in-the-loop simulation environments
- In spite of many challenges in determining thruster on-times which results from the bang-off-bang RCS thruster controller characteristics, this methodology generates results that match with flight results with adequate accuracy
- When averaged over a sample of eight very different RWA bias events, the average difference of on-times between the flight data and the output of this methodology is < 0.6 s, the average difference in Z-axis ΔV is < 0.8 mm/s, and the average difference in hydrazine mass is < 1.1 grams