Evaluation of Fuel-efficient Sun Search Slew Rates for the Cassini Spacecraft in the Cassini Solstice Mission

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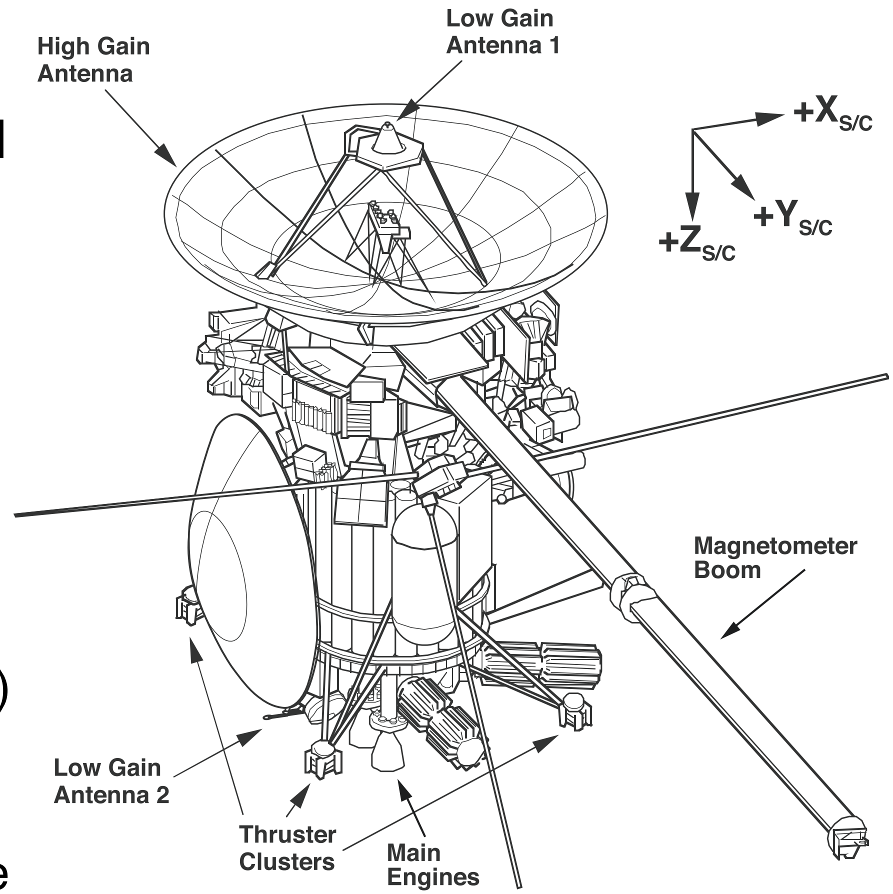
Overview

- Overview of the Cassini Spacecraft
- Hydrazine Consumable Status
- Description of the Cassini Sun Search
- Mathematical Model for the Hydrazine Consumption in the Cassini Sun Search
- Case Study: Anti-Sun Sun Search
- Summary / Conclusions

The Cassini Spacecraft

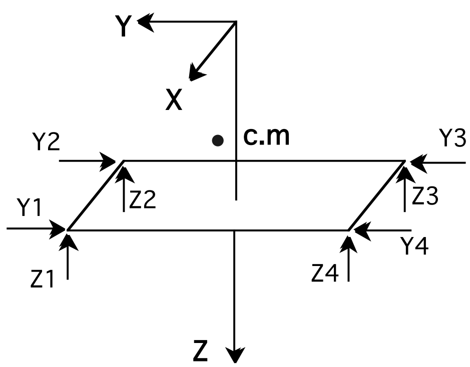
- Launched in 1997 & arrived at Saturn in 2004
- Currently in the Second Extended Mission (the Solstice Mission) scheduled to last until 2017
- 12 science instruments onboard
  - Remote Sensing Instruments
  - Instruments for measuring fields, particles, and plasma waves
- 3-axis stabilized
  - Reaction Wheel Assembly (RWA) control for fine attitude control
  - Reaction Control System (RCS) Thrusters used for coarse attitude control and for reaction wheel momentum dumping



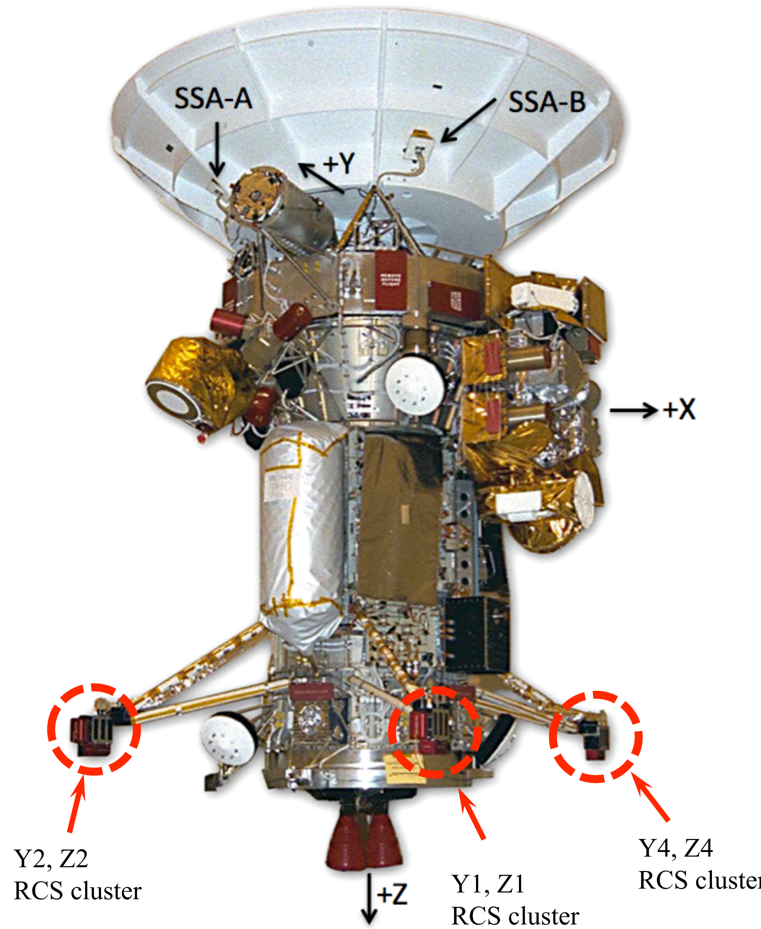
Credits: NASA, JPL

The Cassini Spacecraft

- RCS Thruster Control
  - Two redundant thruster branches
  - Each branch has four Y-facing thrusters and four Z-facing thrusters
  - Attitude control about X & Y axis is performed using Z-facing thrusters
  - Attitude control about Z axis is performed using Y-facing thrusters



- Sun search is performed using RCS thrusters.
- Two Sun sensors are mounted on the high gain antenna with boresight along -Z



* Y3, Z3 RCS cluster not shown

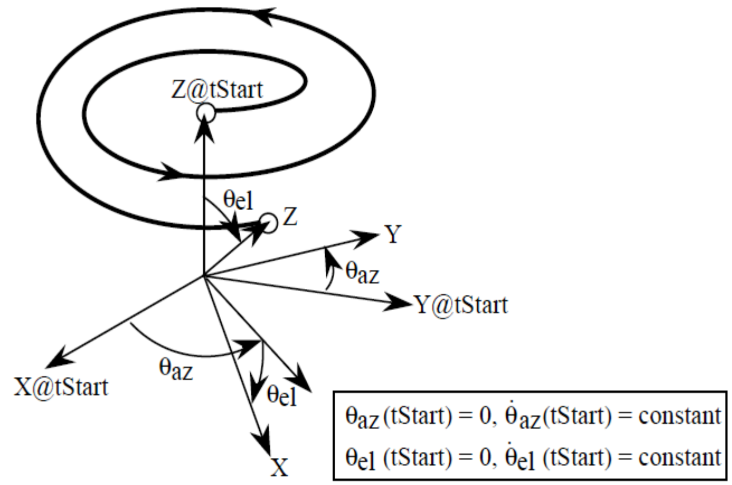
Credits: NASA, JPL

Hydrazine Consumable Status

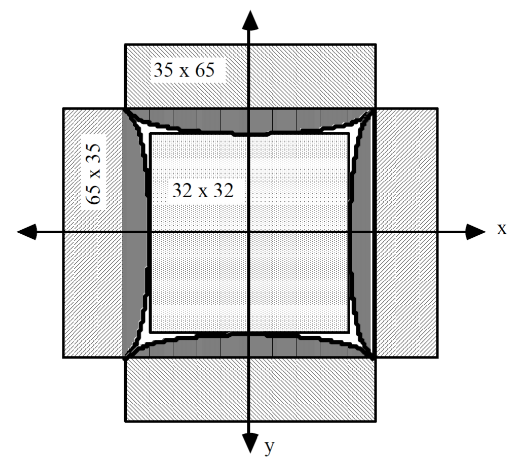
- Hydrazine is used to perform RCS attitude control maneuvers which are crucial for the success of the Cassini mission
  - Small orbit trim maneuvers, Main engine maneuver turns, Reaction wheel biases, Attitude control during close flybys of Titan and Enceladus
  - Sun Search slews
- Hydrazine Consumable Status
  - At the end of the Equinox mission in 2010: 64.6 kg
  - Predicted usage for the Solstice mission: 42.5 kg
    - Contingency maneuvers, safing, and Sun search are not budgeted
  - Unusable hydrazine: up to 10.4 kg
  - Hydrazine margin: less than 12 kg for the remainder of mission
- S/C operators have been trying to minimize frequency of biases. Also a Y-bias strategy is implemented.
- Question: What about Sun search?
  - Sun search has never been initiated up to date. However, ground simulations show that a significant hydrazine could be consumed in the worst Cassini Sun search case, possibly bringing the Cassini mission to a premature end.
- Purpose of this paper is to evaluate fuel efficient Sun search slew rates that reduce hydrazine consumption during Cassini Sun search

Description of the Cassini Sun Search

- Full-sky spiral search pattern achieved by commanding simultaneous rotation about two spacecraft body axes
  - θ_{AZ}: azimuth rotation about the initial S/C Z-axis
  - θ_{EL}: elevation rotation about the rotated Y-axis
- One full-sky 4π steradian Spiral Sun search is completed as θ_{EL} travels 180°
- Under normal operating conditions, Sun will enter ±32° FOV of SSA when elevation angle has rotated ~150°
- If initial Sun search is not successful, then Extended Sun search is invoked and Spiral Sun search pattern is continuously issued.
- During Extended Sun search, different sets of SSA and gyro are tried. Also SSA sensitivity gain is changed after manually set threshold time is passed.

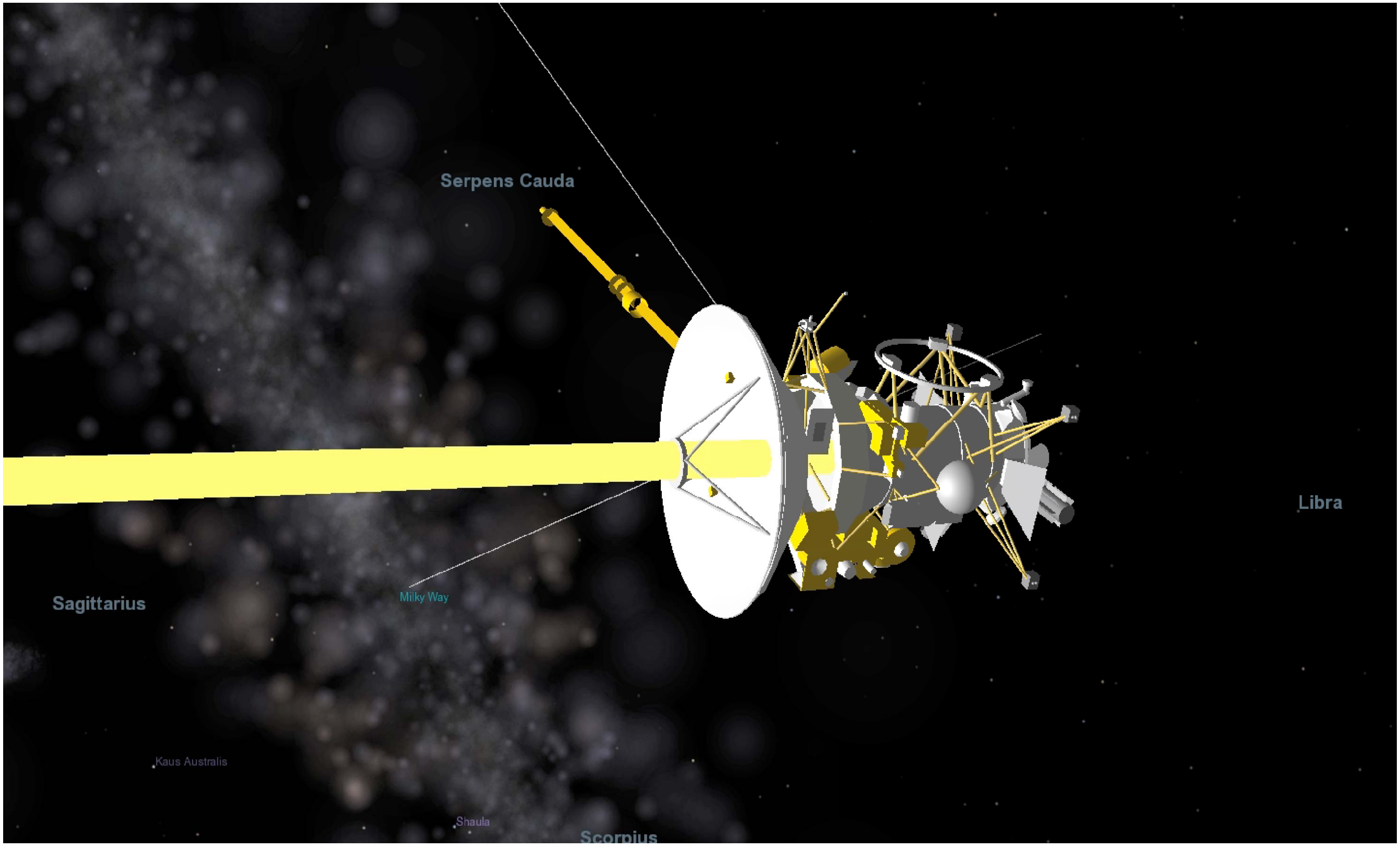


Cassini Spiral Sun Search Pattern



±32° FOV of Sun Sensor

Cassini Sun Search Animation



Mathematical Model for the Hydrazine Consumption in the Cassini Sun Search

- S/C angular body rates and accelerations are given by

$$\vec{\omega}_{S/C} = \begin{bmatrix} -\dot{\theta}_{AZ} \sin\dot{\theta}_{EL} t \\ \dot{\theta}_{EL} \\ \dot{\theta}_{AZ} \cos\dot{\theta}_{EL} t \end{bmatrix} \qquad \dot{\vec{\omega}}_{S/C} = \begin{bmatrix} -\dot{\theta}_{AZ}\dot{\theta}_{EL} \cos\dot{\theta}_{EL} t \\ 0 \\ -\dot{\theta}_{AZ}\dot{\theta}_{EL} \sin\dot{\theta}_{EL} t \end{bmatrix}$$

- Using Euler's equations of motion, the external torque exerted on the S/C can be obtained

$$\begin{bmatrix} \tau_X \\ \tau_Y \\ \tau_Z \end{bmatrix} = \begin{bmatrix} \dot{\theta}_{AZ}\dot{\theta}_{EL}\left(I_{ZZ} - I_{XX} - I_{YY}\right)\cos\dot{\theta}_{EL}t - 2I_{XZ}\dot{\theta}_{AZ}\dot{\theta}_{EL}\sin\dot{\theta}_{EL}t + \dot{\theta}_{AZ}^2 I_{XY}\sin\dot{\theta}_{EL}t\cos\dot{\theta}_{EL}t + \dot{\theta}_{EL}^2 I_{YZ} - \dot{\theta}_{AZ}^2 I_{YZ}\cos^2\dot{\theta}_{EL}t \\ \left(I_{ZZ} - I_{XX}\right)\dot{\theta}_{AZ}^2\sin\dot{\theta}_{EL}t\cos\dot{\theta}_{EL}t - I_{XZ}\dot{\theta}_{AZ}^2\left(\cos^2\dot{\theta}_{EL}t - \sin^2\dot{\theta}_{EL}t\right) \\ \dot{\theta}_{AZ}\dot{\theta}_{EL}\left(I_{XX} - I_{YY} - I_{ZZ}\right)\sin\dot{\theta}_{EL}t - 2I_{XZ}\dot{\theta}_{AZ}\dot{\theta}_{EL}\cos\dot{\theta}_{EL}t + \dot{\theta}_{AZ}^2 I_{XY}\sin^2\dot{\theta}_{EL}t - \dot{\theta}_{AZ}^2 I_{YZ}\sin\dot{\theta}_{EL}t\cos\dot{\theta}_{EL}t - \dot{\theta}_{EL}^2 I_{XY} \end{bmatrix}$$

- Total hydrazine consumption for Cassini Sun search can be obtained using the following expression

$$C_f = \frac{\int_0^T |\tau_X| dt}{L_Y I_{SP}} + \frac{\int_0^T |\tau_Y| dt}{L_X I_{SP}} + \frac{\int_0^T |\tau_Z| dt}{L_X I_{SP}}$$

Case Study: Anti-Sun Sun Search

- A spiral Sun search is commanded from the anti-Sun position where FOV of Sun sensor is pointed directly opposite to the Sun.
  - Angular distance that S/C has to slew to find the Sun is the largest
- Hydrazine consumption for one full-sky Sun search due to dominant external torque terms (moment of inertia terms) is given by

$$C_{f\_anti\_Sun\_appx} = C_{f\_anti\_Sun\_appx\_X} + C_{f\_anti\_Sun\_appx\_Y} + C_{f\_anti\_Sun\_appx\_Z}$$

$$C_{f\_anti\_Sun\_appx\_X} = \left| \frac{2\left(I_{ZZ} - I_{XX} - I_{YY}\right)\dot{\theta}_{AZ}}{L_Y I_{SP}} \right|$$

$$C_{f\_anti\_Sun\_appx\_Y} = \left| \frac{\left(I_{ZZ} - I_{XX}\right)\dot{\theta}_{AZ}^2}{\dot{\theta}_{EL} L_X I_{SP}} \right|$$

$$C_{f\_anti\_Sun\_appx\_Z} = \left| \frac{2\left(I_{XX} - I_{YY} - I_{ZZ}\right)\dot{\theta}_{AZ}}{L_X I_{SP}} \right|$$

- Hydrazine consumption for slews about both X-axis and Z-axis are proportional to $\dot{\theta}_{AZ}$
- Hydrazine consumption for slew about Y-axis is proportional to $\frac{\dot{\theta}_{AZ}^2}{\dot{\theta}_{EL}}$
- Therefore, decreasing $\dot{\theta}_{AZ}$, and increasing $\dot{\theta}_{EL}$ will reduce hydrazine consumption

Anti-Sun Search: Choosing Fuel-efficient Slew Rates

- Current default rate
  - 6.990 mrad/s for azimuth, 1.165 mrad/s for elevation

- Constraint #1: Azimuth rate constraint
  - Boresights of temperature-sensitive science instruments must move fast enough to avoid potential prolonged Sun exposure

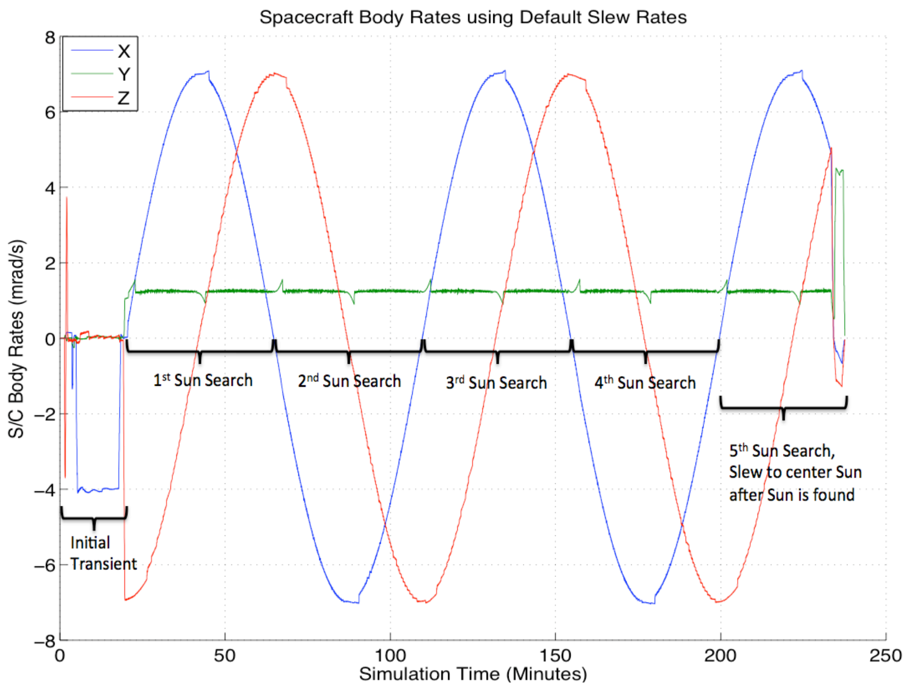
$$\left|\dot{\theta}_{AZ}\right| \geq 3.33 \text{ mrad/s}$$

- Constraint #2: Full-sky coverage must be provided

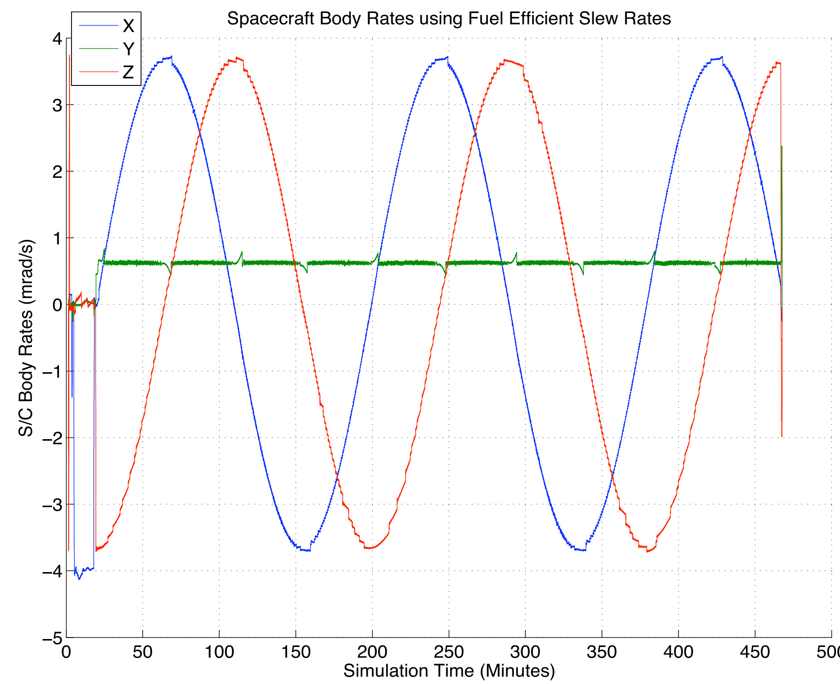
$$\left|\frac{\dot{\theta}_{AZ}}{\dot{\theta}_{EL}}\right| \geq 6$$

- Fuel-efficient slew rate proposed
  - 3.495 mrad/s for azimuth, 0.5825 mrad/s for elevation

Anti-Sun Search Simulation Results: Body Rates

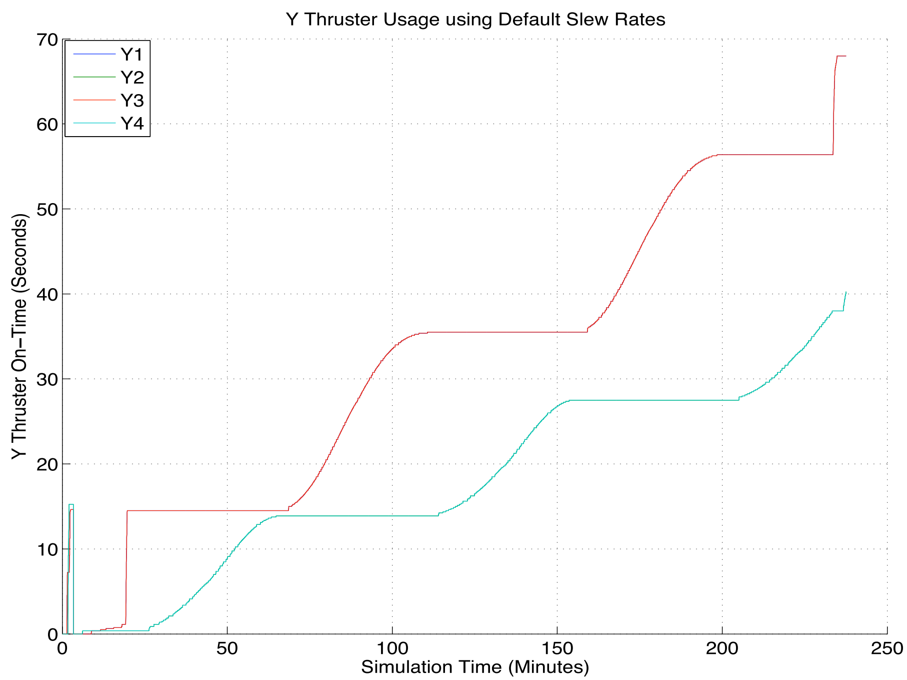


S/C Body Rates using Default Slew Rates

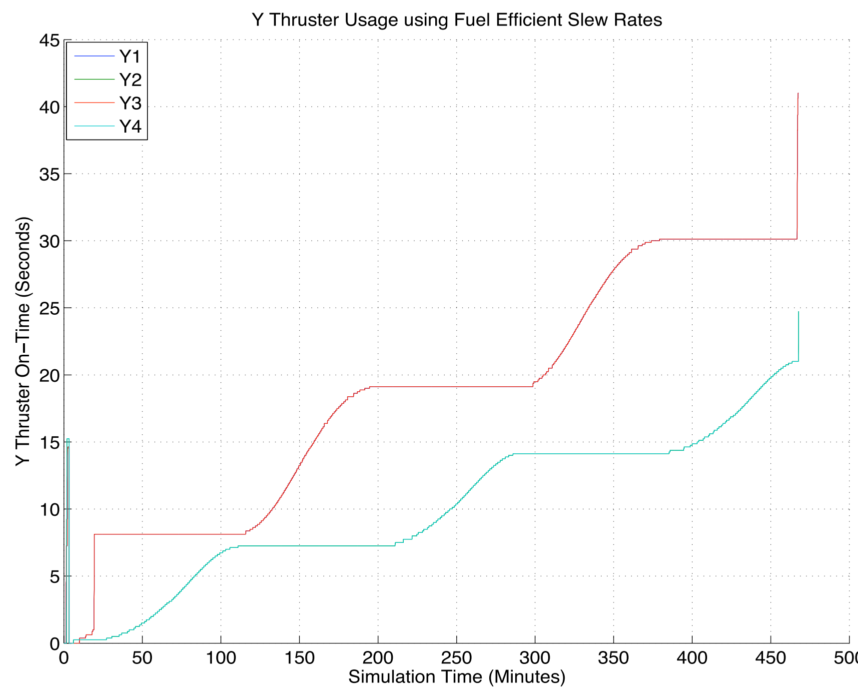


S/C Body Rates using Fuel-efficient Slew Rates

Anti-Sun Search Simulation Results: Y thruster On-times

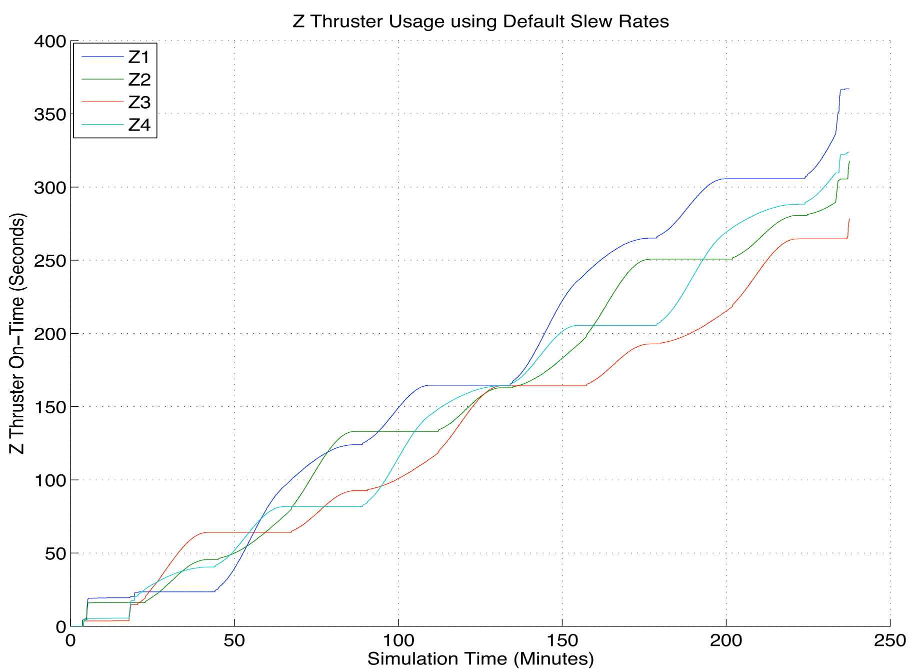


Y Thruster On-times using Default Slew Rates

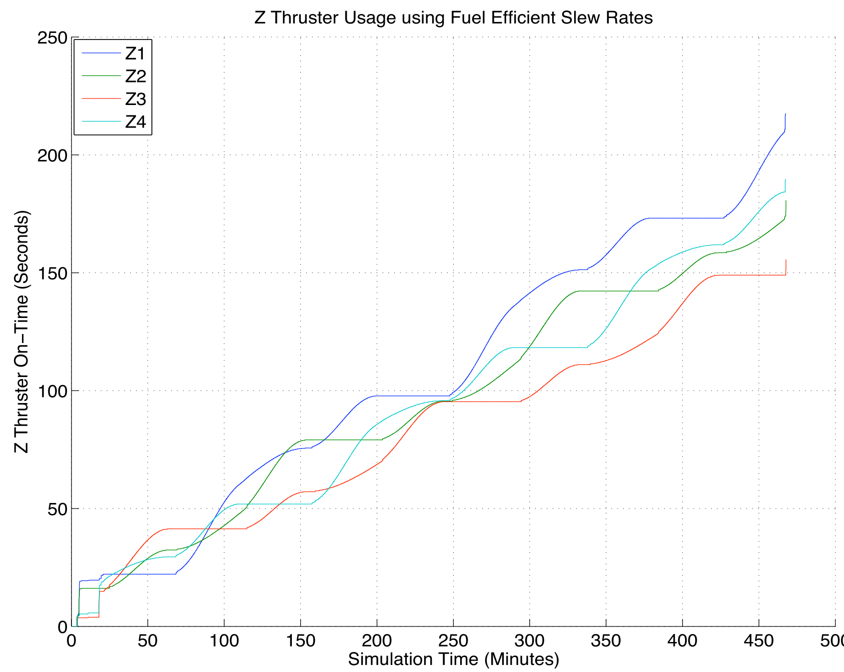


Y Thruster On-times using Fuel-efficient Slew Rates

Anti-Sun Search Simulation Results: Z thruster On-times



Z Thruster On-times using Default Slew Rates



Z Thruster On-times using Fuel-efficient Slew Rates

Anti-Sun Search Results Summary

- Fuel cost from thruster on-times can be computed using:

$$C_{f\,on\_time} = \frac{T_{ON\_TIME} \times F_{Thruster}}{I_{SP}}$$

- Theoretical results match with Simulation results within:
  - 9.1% for the hydrazine consumption due to Y-thruster firings
  - 4.3% for the hydrazine consumption due to Z-thruster firings

- Fuel-efficient slew rates produce a greater than 45% (or greater than 0.049 kg) saving in hydrazine consumption per one full-sky Sun search

	Using Default Slew Rates	Using Fuel-efficient Slew Rates
Theoretical Fuel Cost from Y-thruster Firings, kg	0.012	0.0059
Theoretical Fuel Cost from Z-thruster Firings, kg	0.099	0.0495
Theoretical Total Fuel Cost, kg	0.111	0.0554
Simulation Fuel Cost from Y-thruster Firings. Kg	0.011	0.0055
Simulation Fuel Cost from Z-thruster Firings, kg	0.095	0.0513
Simulation Total Fuel Cost, kg	0.106	0.0568
Theory vs Sim % Diff Fuel Cost Y-thruster Firings, %	9.09	7.27
Theory vs Sim % Diff Fuel Cost Z-thruster Firings, %	4.21	3.51
Theory vs Sim % Diff Total Fuel Cost, %	4.72	2.46
Fuel Cost Saving using Fuel-efficient Slew Rates, %		46.4

Summary and Conclusions

- With approximately 5 years remaining in the second extended mission, it is critical to save hydrazine and maintain adequate hydrazine margin to ensure a successful conclusion of the Cassini mission
- A hydrazine saving of greater than 45% could be achieved by simply using slower fuel-efficient rates during Sun search
- The costs and benefits, as well as the risks, incurred by these potential changes need to be carefully examined before the actual implementation onboard the Cassini spacecraft

Backup Slides

Full Analytical Expression for Hydrazine Consumption

- Hydrazine consumption for one full-sky Sun search is given by

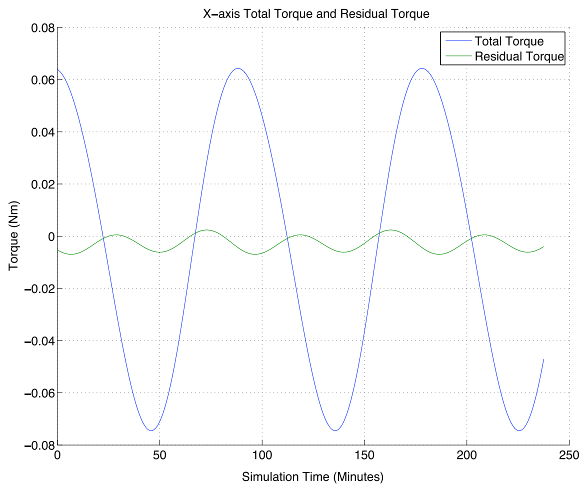
$$C_{f\_anti\_Sun} = C_{f\_anti\_Sun\_X} + C_{f\_anti\_Sun\_Y} + C_{f\_anti\_Sun\_Z}$$

$$C_{f\_anti\_Sun\_X} = \left| \frac{2\left(I_{ZZ} - I_{XX} - I_{YY}\right)\dot{\theta}_{AZ}}{L_Y I_{SP}} + \frac{\dot{\theta}_{AZ}^2 I_{XY}}{\dot{\theta}_{EL} L_Y I_{SP}} \right|$$

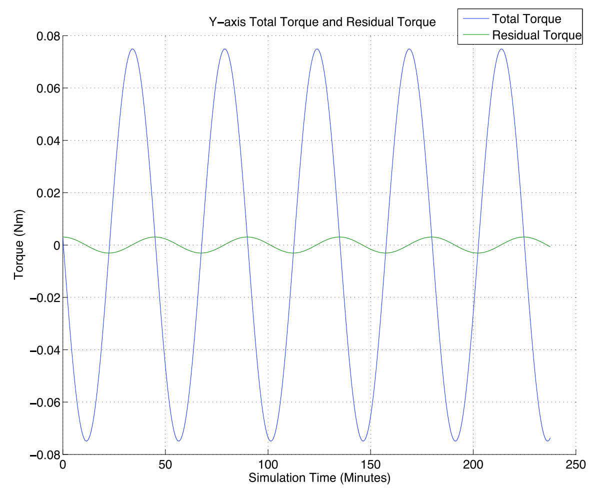
$$C_{f\_anti\_Sun\_Y} = \left| \frac{\left(I_{ZZ} - I_{XX}\right)\dot{\theta}_{AZ}^2}{\dot{\theta}_{EL} L_X I_{SP}} \right|$$

$$C_{f\_anti\_Sun\_Z} = \left| \frac{2\left(I_{XX} - I_{YY} - I_{ZZ}\right)\dot{\theta}_{AZ}}{L_X I_{SP}} + \frac{\pi I_{XY}}{2\dot{\theta}_{EL} L_X I_{SP}}\left(\dot{\theta}_{AZ}^2 - 2\dot{\theta}_{EL}^2\right) \right|$$

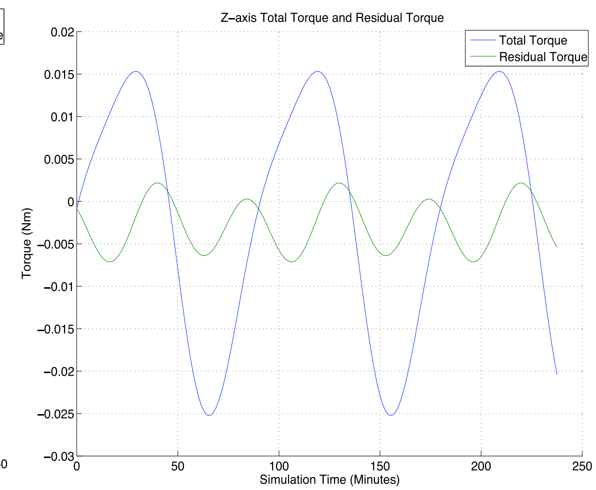
Effects of Residual Torque Terms



X-axis Total Torque and Residual Torque



Y-axis Total Torque and Residual Torque



Z-axis Total Torque and Residual Torque

S/C Inertia Matrix used

$$I_{S/C} = \begin{bmatrix} 6597.64 & -119.58 & -62.54 \\ -119.58 & 5426.70 & 110.24 \\ -62.54 & 110.24 & 3534.34 \end{bmatrix}$$

<u>*Sign Convention used for S/C Inertia*</u>

$$I = \begin{bmatrix} I_{XX} & I_{XY} & I_{XZ} \\ I_{YX} & I_{YY} & I_{YZ} \\ I_{ZX} & I_{ZY} & I_{ZZ} \end{bmatrix}$$

$$I_{XX} = \int_m \left(y^2 + z^2\right) dm \qquad I_{XY} = I_{YX} = -\int_m xy\, dm$$

$$I_{YY} = \int_m \left(x^2 + z^2\right) dm \qquad I_{YZ} = I_{ZY} = -\int_m yz\, dm$$

$$I_{ZZ} = \int_m \left(x^2 + y^2\right) dm \qquad I_{XZ} = I_{ZX} = -\int_m xz\, dm$$