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Skimming through Saturn's Atmosphere: The Climax of the Cassini Grand Finale Mission

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Objective of Study

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- Between August 14 and September 9 of 2017, Cassini flew 5 orbits with periapses that skimmed Saturn's atmosphere
- Engineering and science data was transmitted back to Earth after every periapsis
- Using thruster on-time data, as well as other Attitude Control Subsystem (ACS) telemetry, a method of reconstructing Saturn's atmosphere for Rev-288 through Rev-292 is proposed, and results are presented

Cassini Spacecraft

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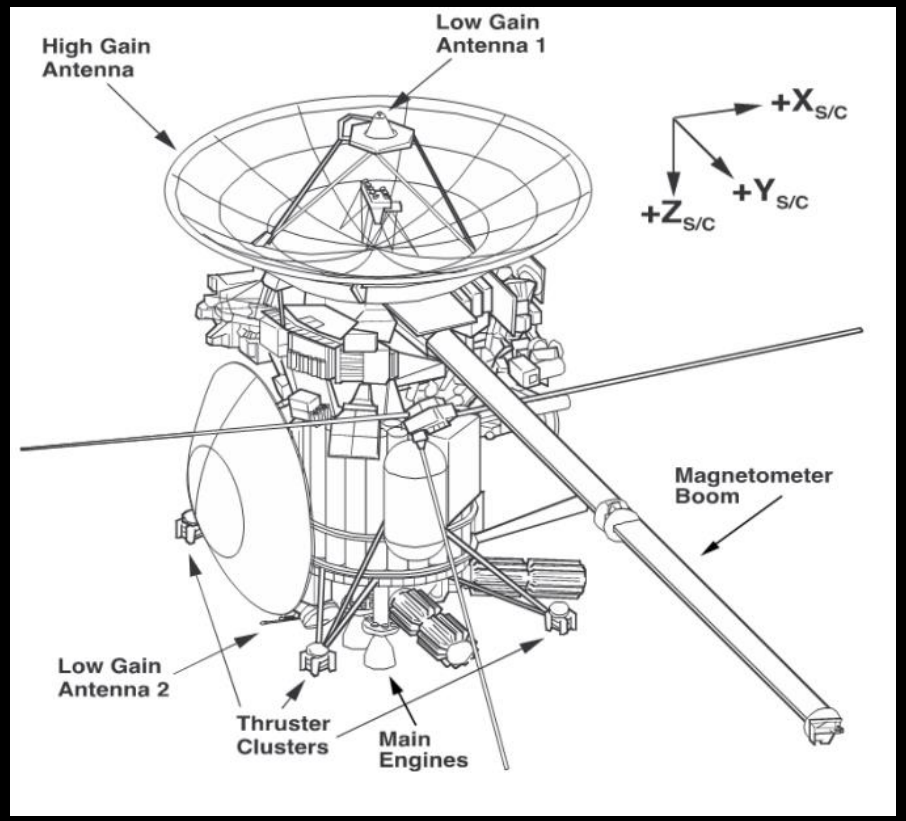
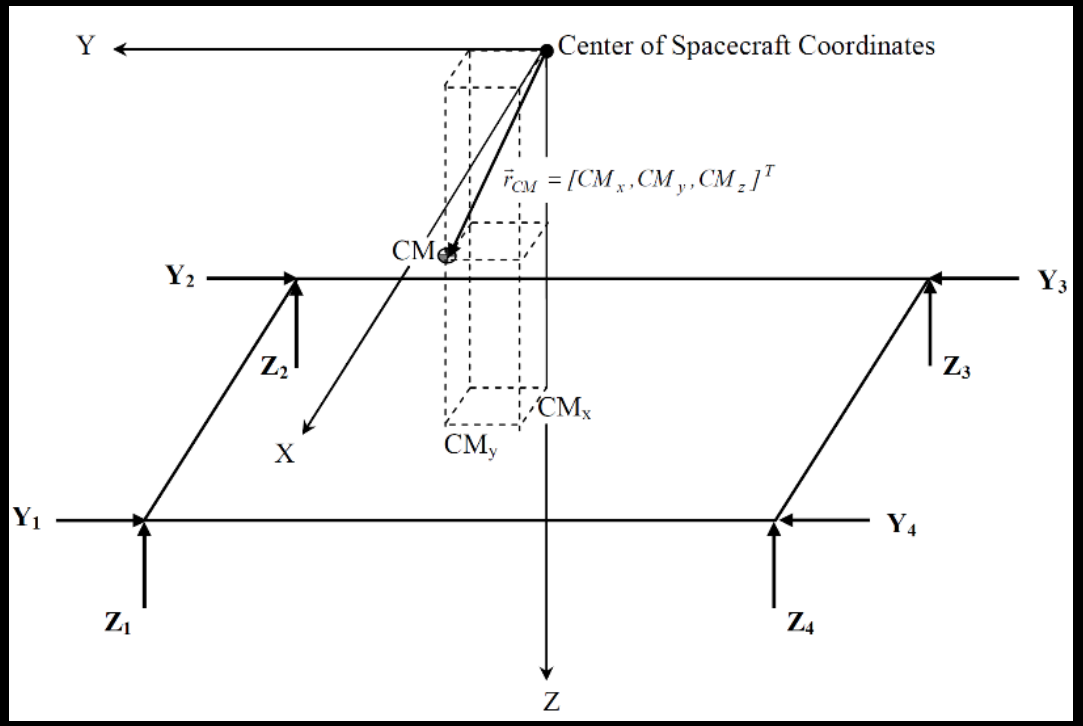
Overview of Cassini S/C



RCS Thruster Placement



Final Five Orbit's Around Saturn

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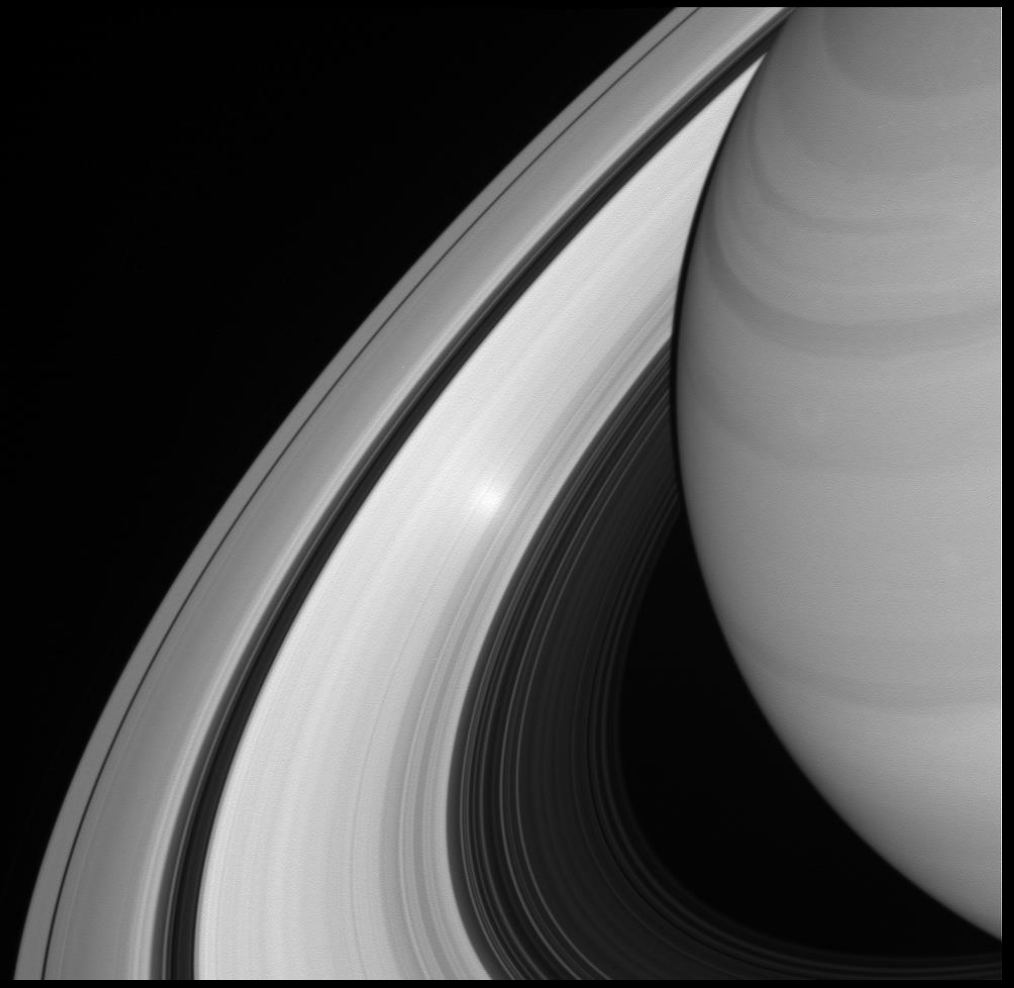
- Apr 22: T-126 Titan flyby
  - Beginning of 22 Proximal Orbits
  - 9 non-targeted Titan flybys
- Jul 15: OTM-472 Maneuver
- Aug 14: Rev-288
- Aug 20: Rev-289
- Aug 27: Rev-290
- Sep 2: Rev-291
- Sep 9: Rev-292
- Sep 11: Last non-targeted Titan flyby
- Sep 15: Saturn impact



https://saturn.jpl.nasa.gov/resources/7491/?category=images

Contingency Orbit Trim Maneuver

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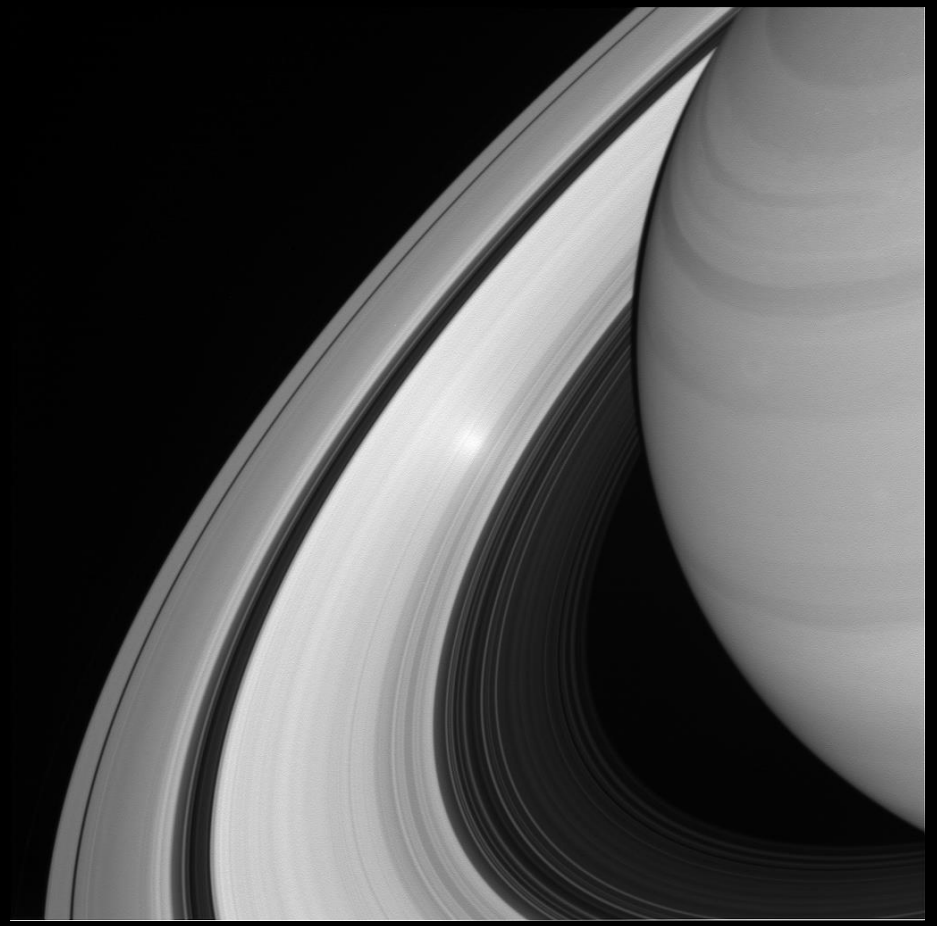
- Understanding density of Saturn atmosphere was important for (1) scientific purposes and (2) spacecraft health and safety
- Before Rev-288, the atmosphere of Saturn was uncertain
- Contingency pop-up maneuver to raise altitude
- Contingency pop-down maneuver to raise altitude
- Thruster duty-cycle analysis: 10% - 60% comfortable range



https://saturn.jpl.nasa.gov/resources/7491/?category=images

Predicted Duty Cycles

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Rev	Periapsis Date	Minimum Altitude* km	Y-Thrusters %	Z-Thrusters %
288	14 August 2017	1706	9.25	4.39
289	20 August 2017	1652	11.65	21.00
290	27 August 2017	1626	14.96	7.51
291	2 September 2017	1639	13.95	6.75
292	9 September 2017	1675	12.33	7.64

* Altitude defined as distance above the Saturn radius at which atmospheric pressure is equivalent to 1-bar

Actual Duty Cycles

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Rev	Periapsis Date	Minimum Altitude* km	Y-Thrusters %	Z-Thrusters %
288	14 August 2017	1706	29.7	10.9
289	20 August 2017	1652	33.3	44.0
290	27 August 2017	1626	40.6	15.0
291	2 September 2017	1639	41.0	14.5
292	9 September 2017	1675	25.8	9.5

* Altitude defined as distance above the Saturn radius at which atmospheric pressure is equivalent to 1-bar

“Thruster On-Time” Density Reconstruction Method

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- Method originally developed for estimating Titan atmospheric density
  - Based on conservation of angular momentum: 1) estimate atmospheric torque, and 2) estimate atmospheric density
- Limitations of Method: 1) Center of pressure uncertainty, 2) method assumes inbound and outbound flight data

$$\rho = \frac{2\vec{T}_{Atm}}{C_D V^2 A_{proj} \hat{u}_V \times (\vec{r}_{CP} - \vec{r}_{CM})}$$

- $\vec{T}_{Atm}$ = atmospheric torque, Nm
- C_D = drag coefficient, dimensionless
- ρ = atmospheric density, kg/m^3
- V = magnitude of S/C velocity relative to rotating Saturn, m/s
- A_{Proj}= S/C projected area, m^2
- $\hat{u}_V$ = unit vector of S/C velocity expressed in S/C body frame
- $\vec{r}_{CM}$= position vector of S/C’s center of mass relative to S/C coordinate frame origin, m

*Details of reconstruction method are found in Ref. 5 and 8 of the full paper

Rev-288 Accumulated Angular Momentum

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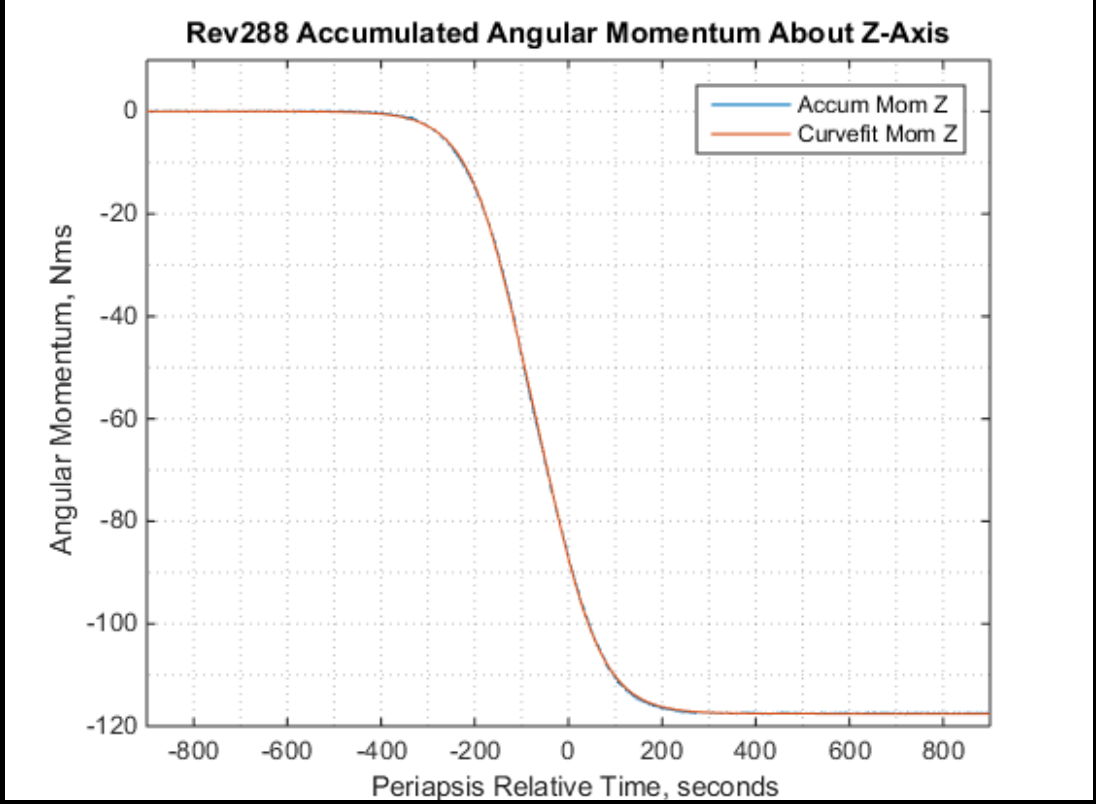

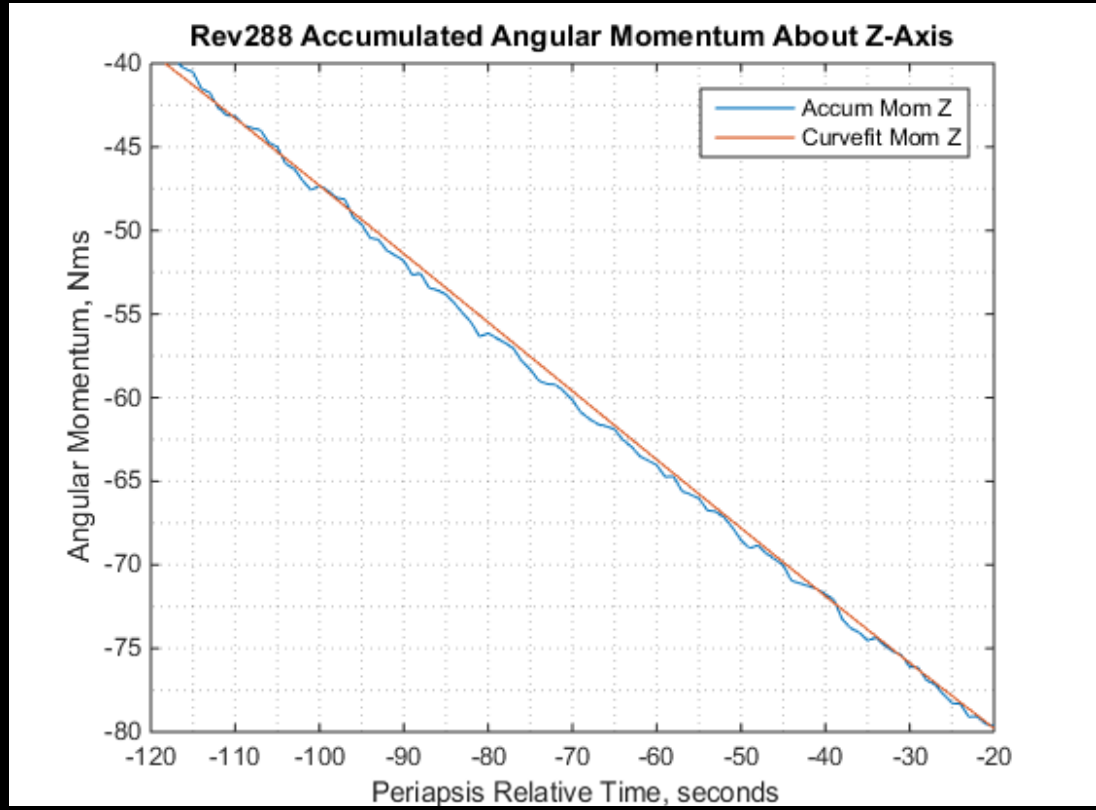

Rev-288 Atmospheric Torque and Density

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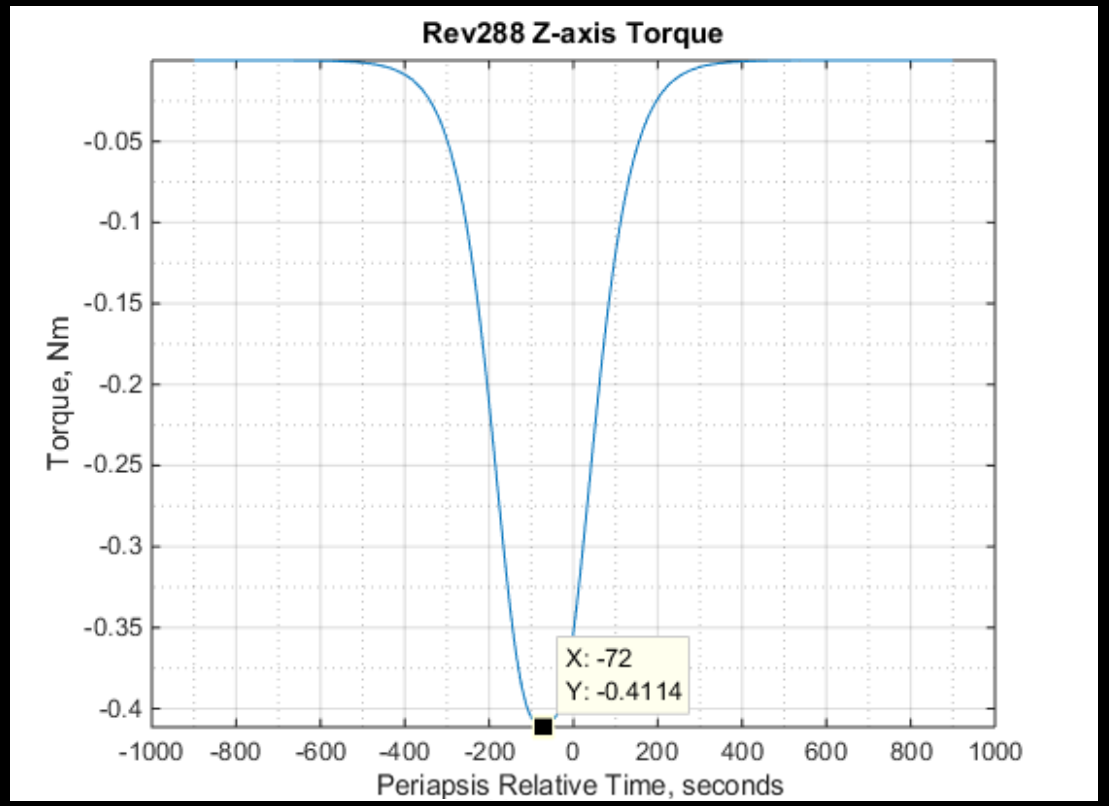

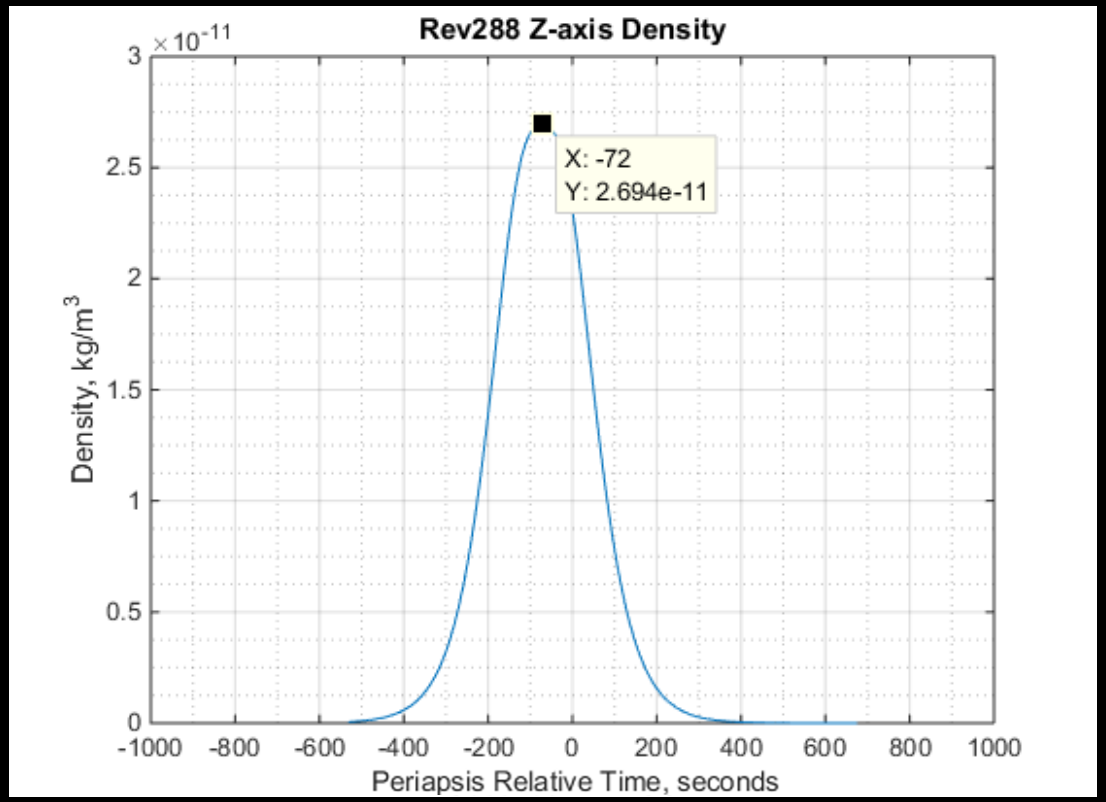

Rev288-292 Flyby Attitudes

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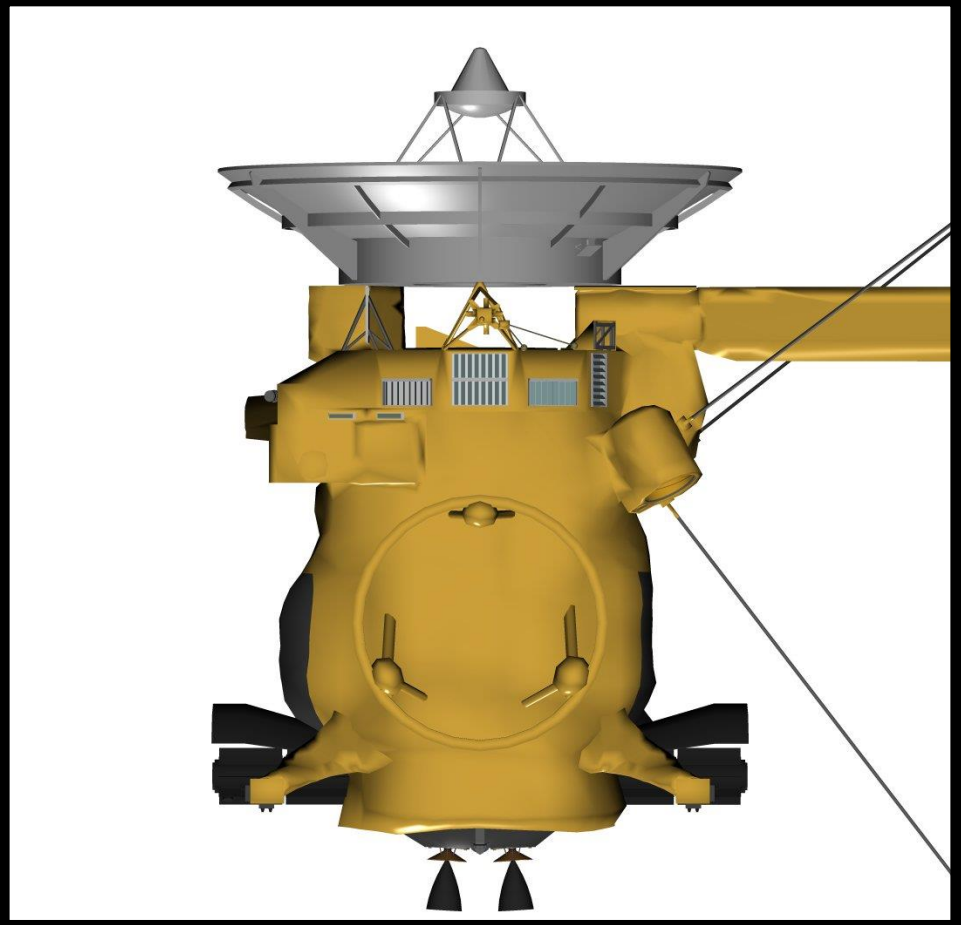
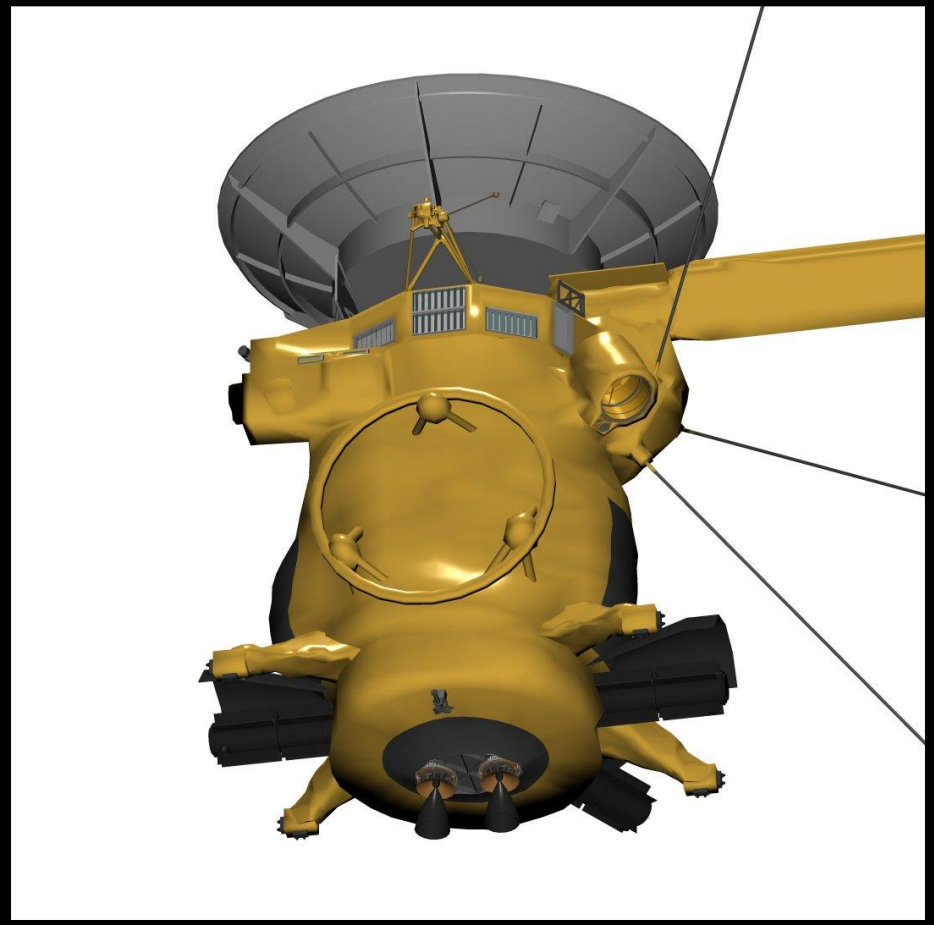
Rev288 S/C Orientation at Periapsis



Rev289 S/C Orientation at Periapsis



Rev288-292 Flyby Attitudes

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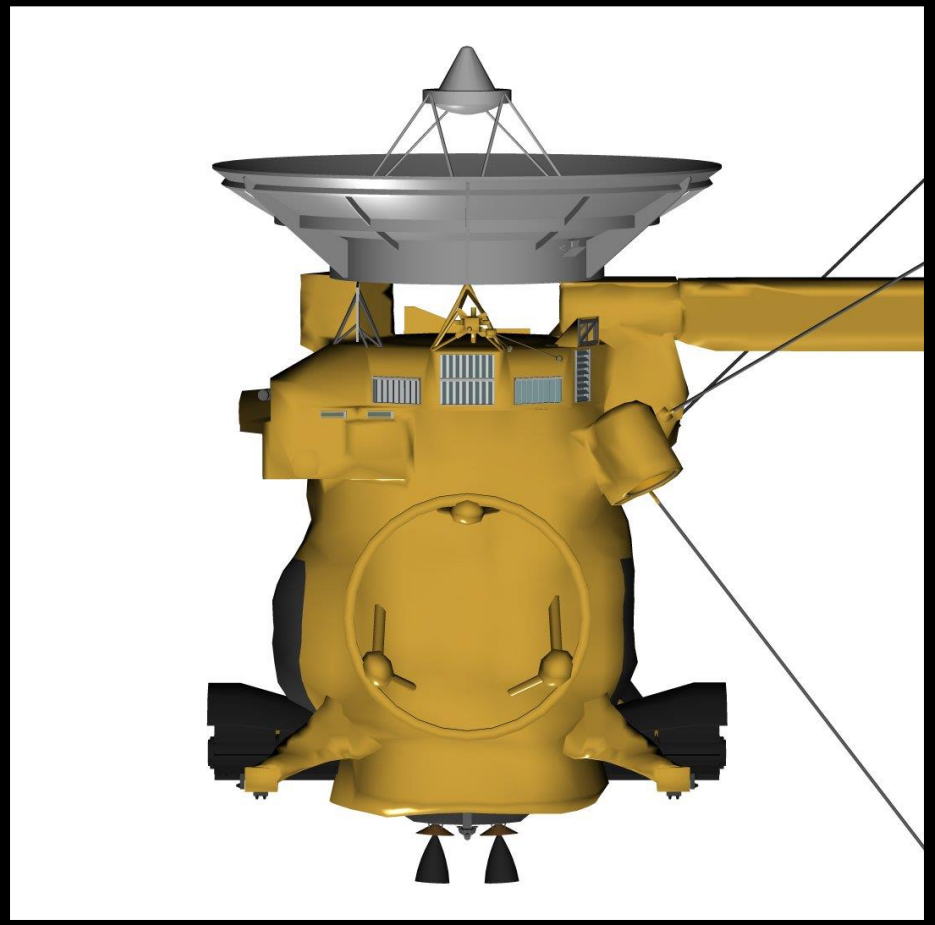
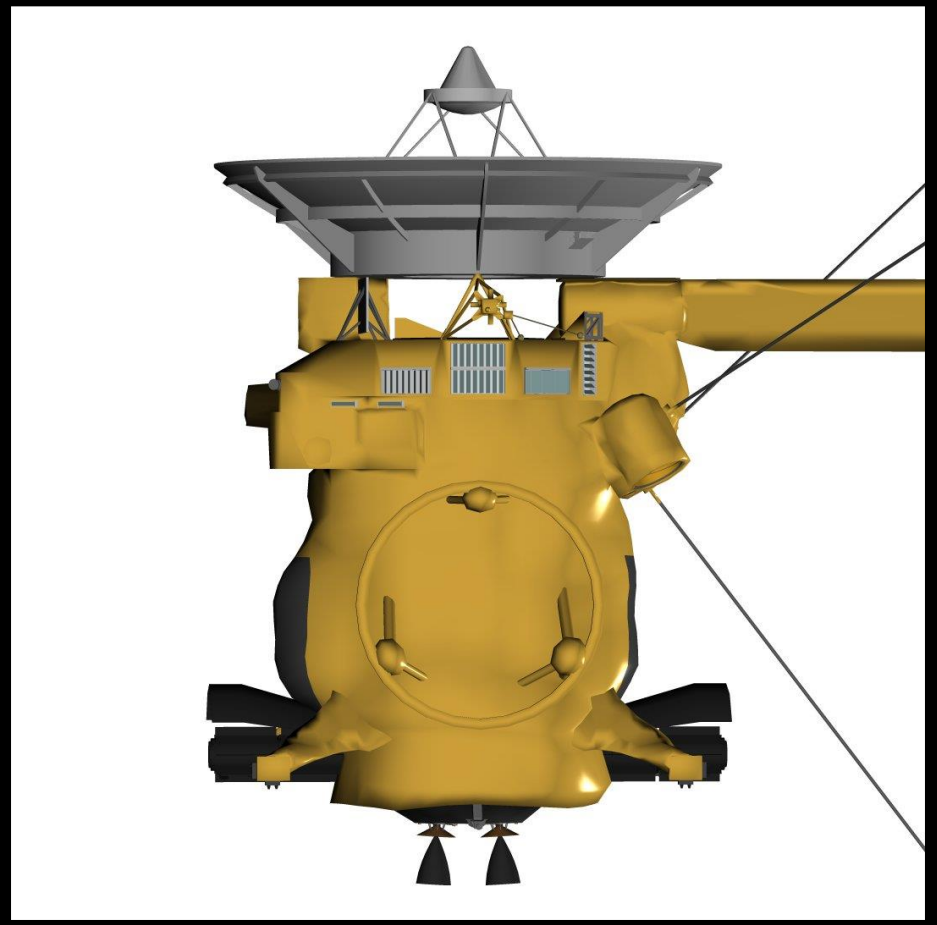
Rev290 S/C Orientation at Periapsis



Rev291 S/C Orientation at Periapsis



Rev288-292 Flyby Attitudes

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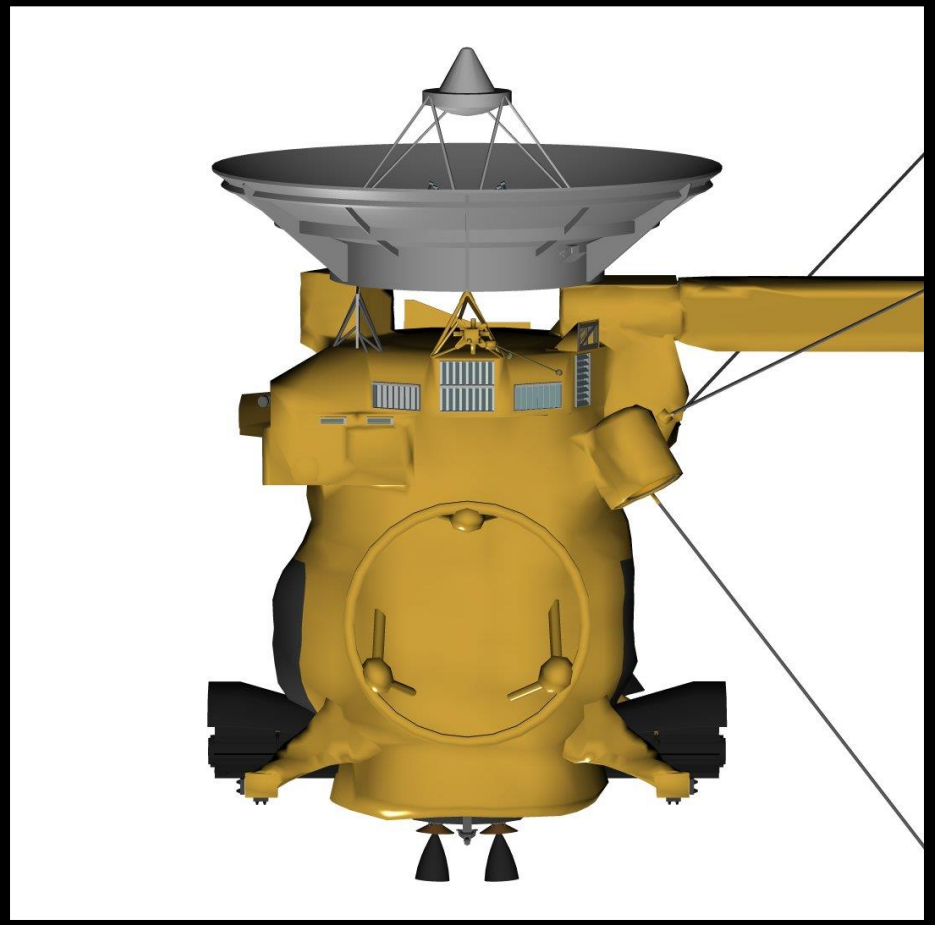
Rev292 S/C Orientation at Periapsis



- Rev-289 had a different science attitude at periapsis, which increased the effective CP-CM moment arm, resulting in larger duty cycles for the Z1, Z3, and Z4 thrusters

Rev288-292 Duty Cycle Profiles

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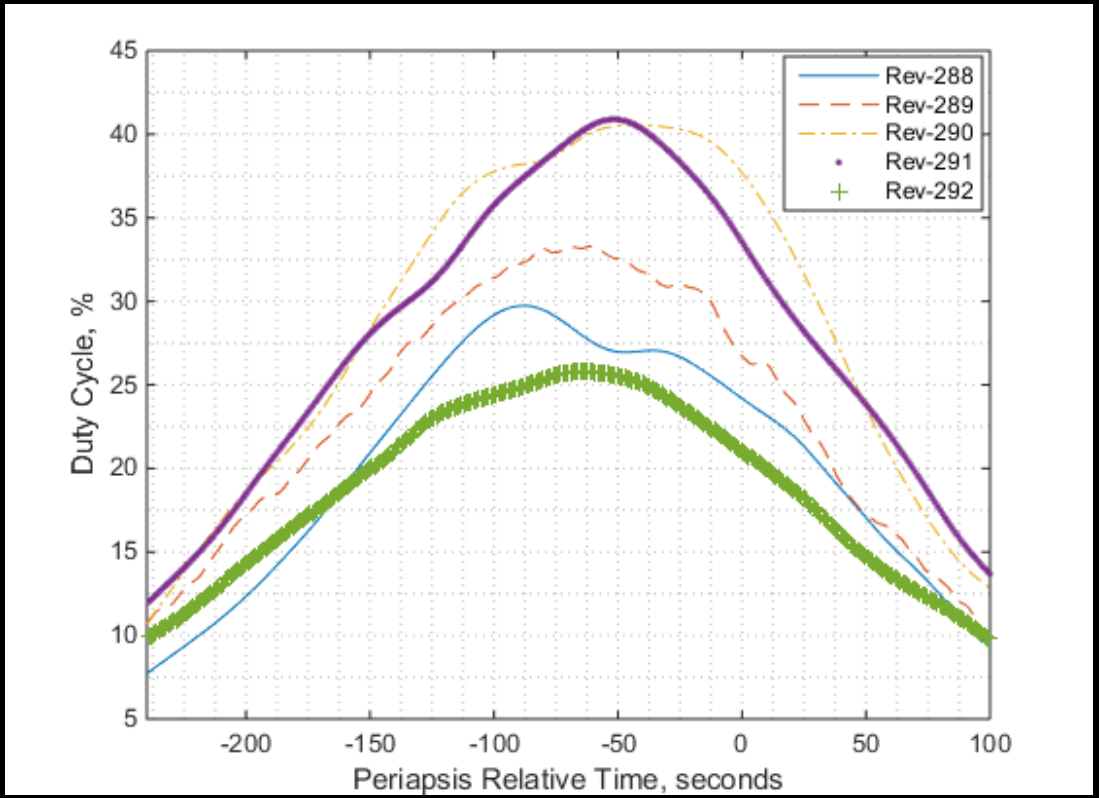
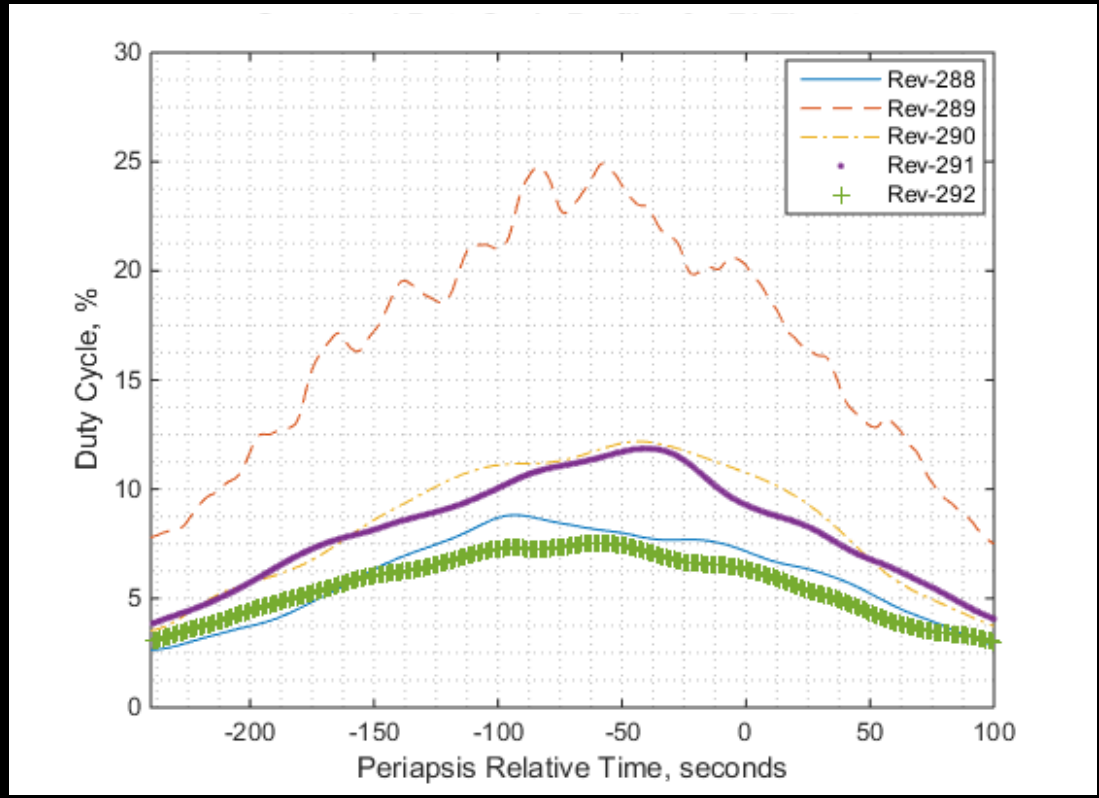
Smoothed Duty Cycle Profiles for Y2/Y4 Thruster



Smoothed Duty Cycle Profiles for Y2/Y4 Thruster



Rev288-292 Duty Cycle Profiles

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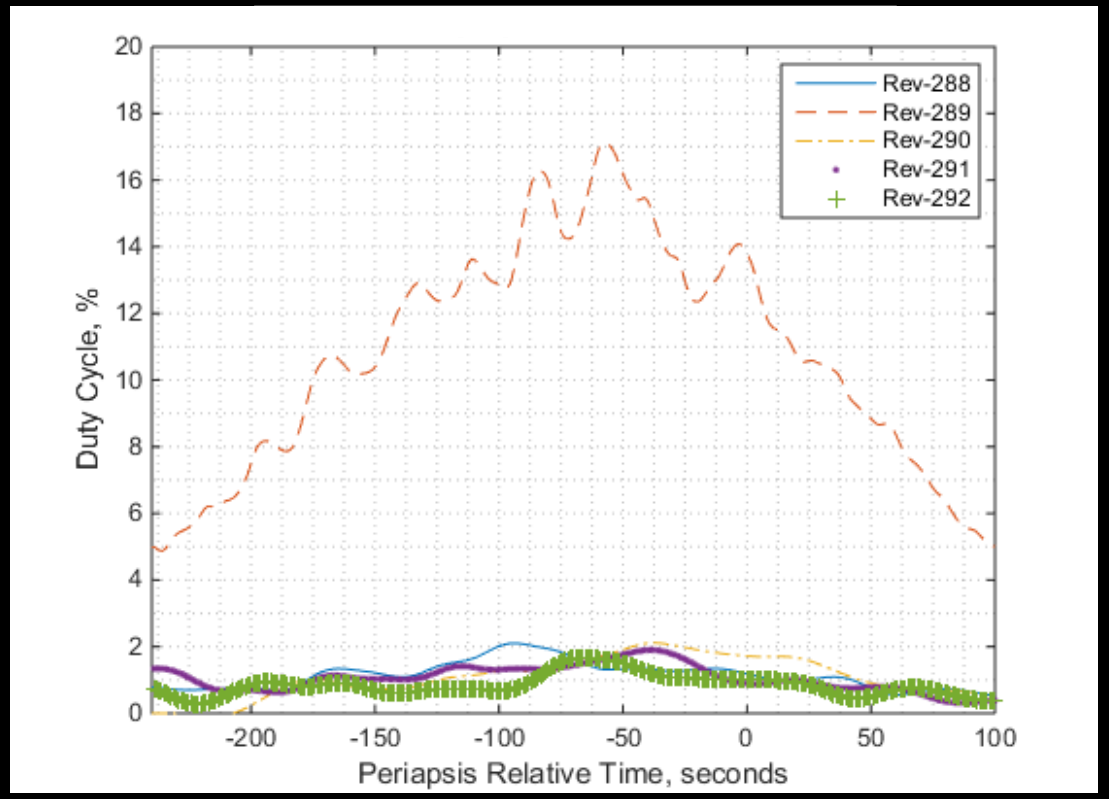
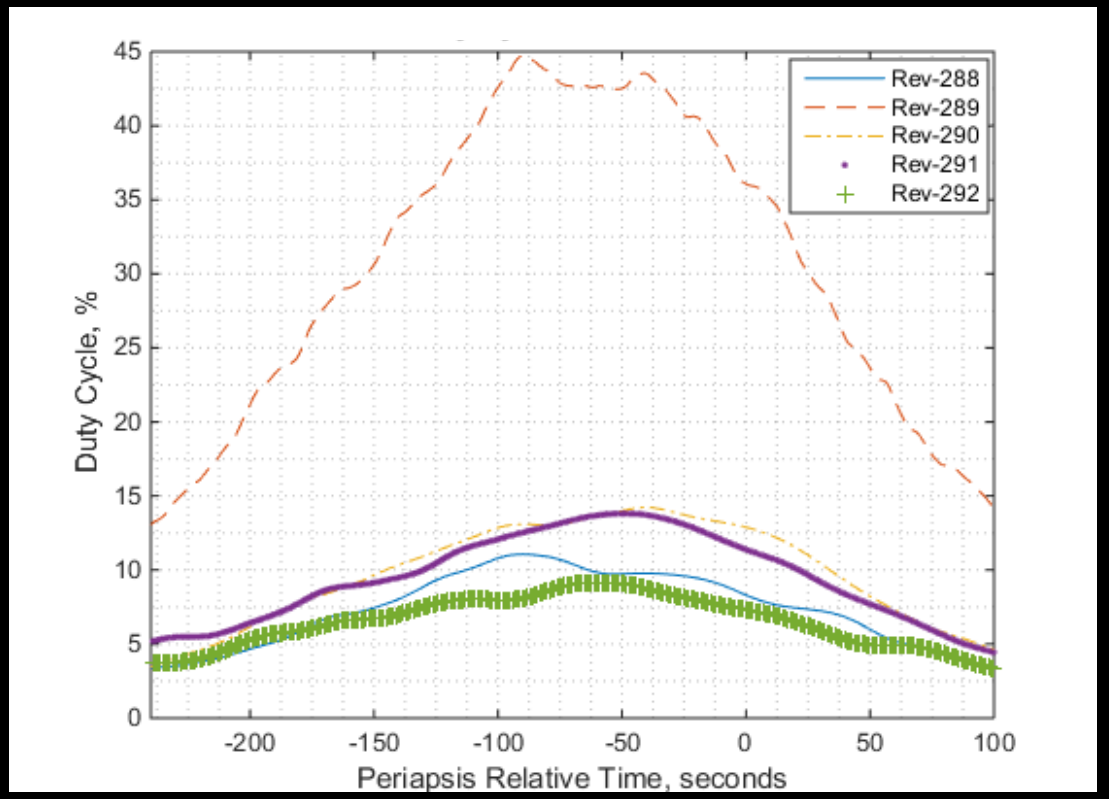
Smoothed Duty Cycle Profiles for Z3 Thruster



Smoothed Duty Cycle Profiles for Z4 Thruster



Rev288-292 Flyby Altitude an Atmospheric Torque Profiles

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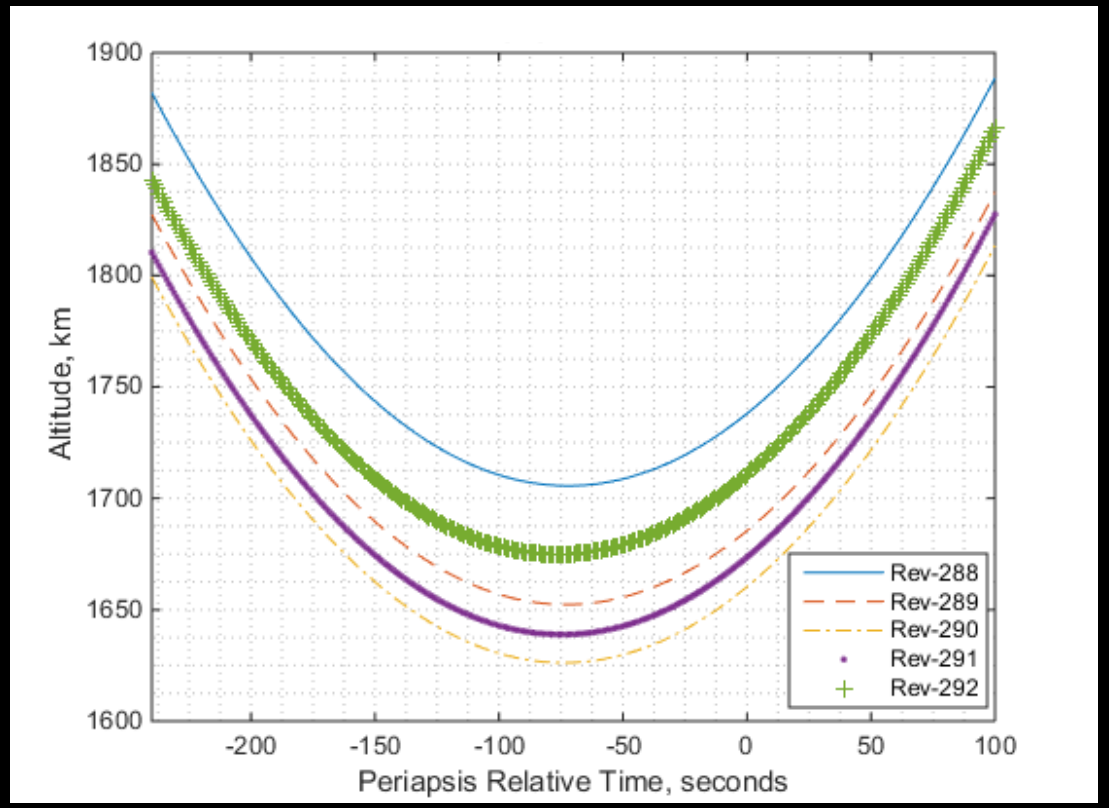
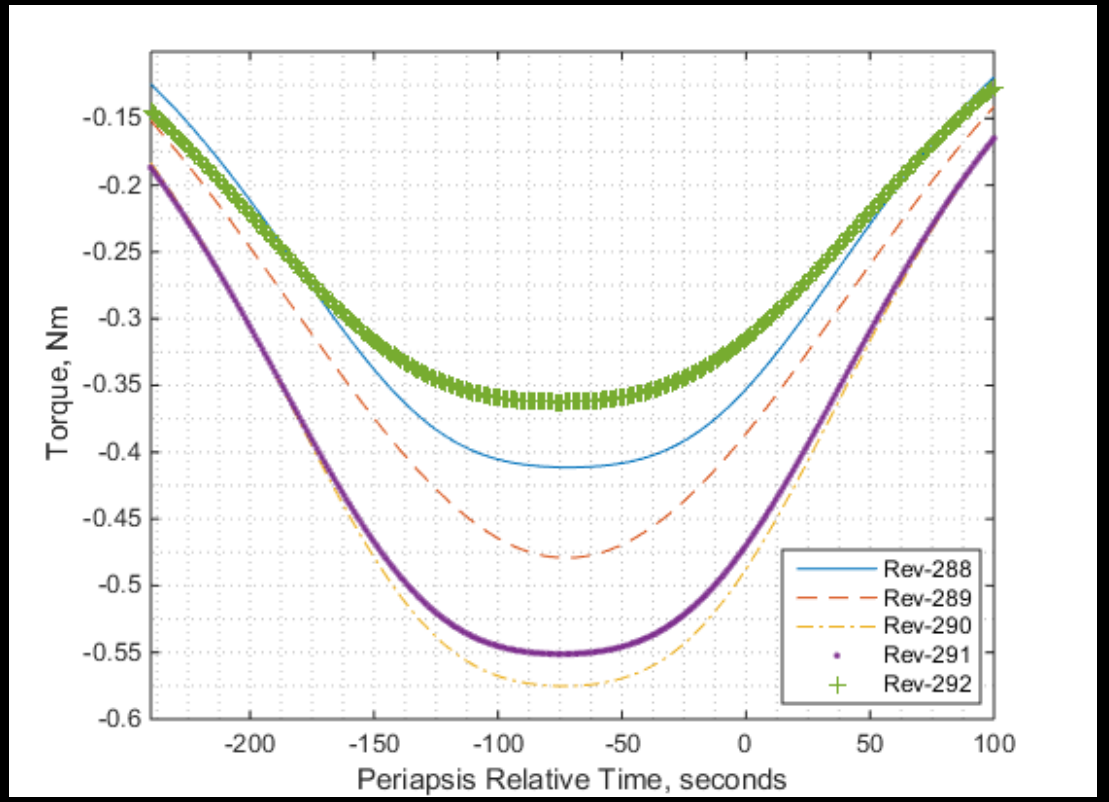
Flyby Altitude



Z-axis Torque



Rev288-292 Atmospheric Density

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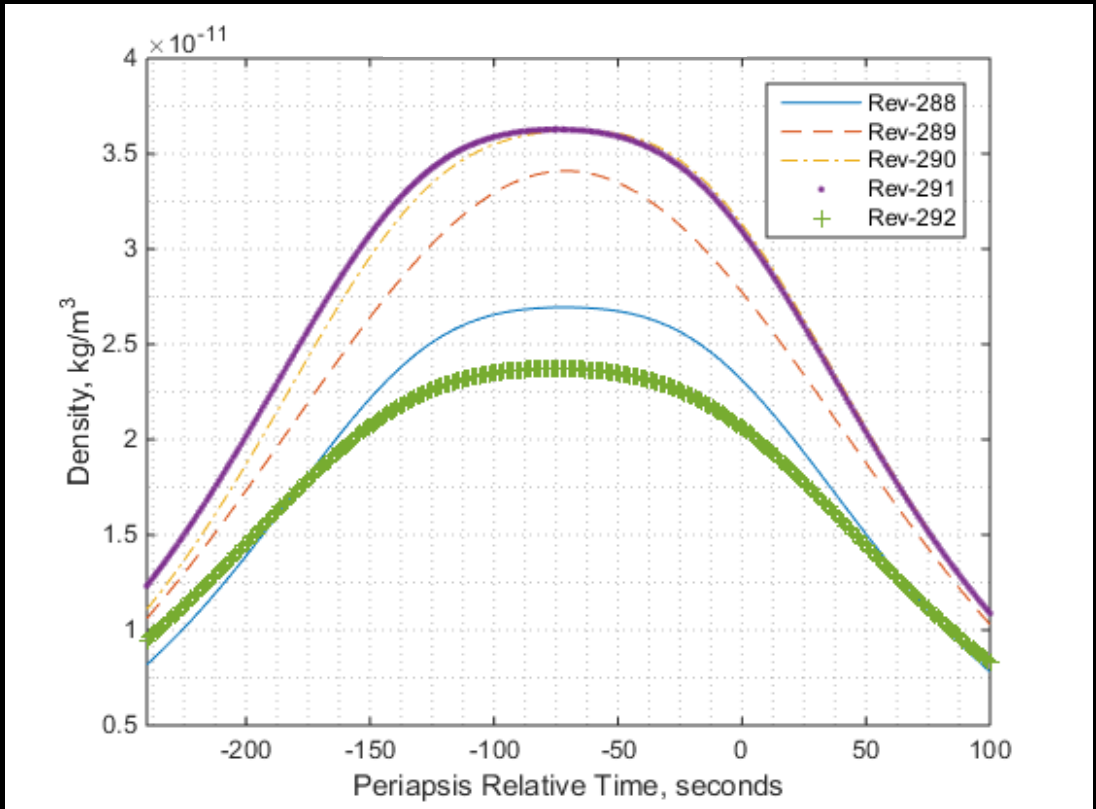
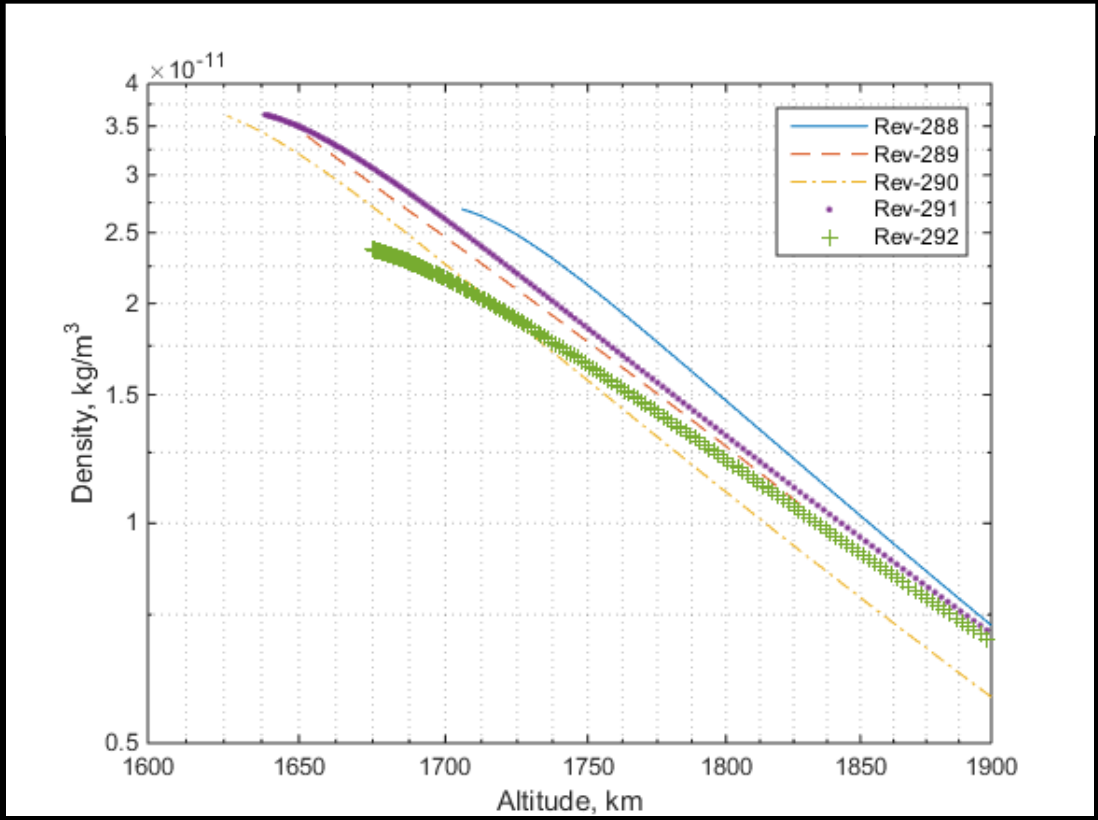
Z-axis Density



Inbound Density vs Altitude



Summary of Final Five Orbits

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Rev	Periapsis Date	Periapsis Time SCET	Min Altitude* km	Y-Thrusters %	Z-Thrusters %	Peak Density kg/m^3
288	14 August 2017	226T04:23:02	1706	29.7	10.9	2.6939e-11
289	20 August 2017	232T15:23:00	1652	33.3	44.0	3.4097e-11
290	27 August 2017	239T02:18:10	1626	40.6	15.0	3.6244e-11
291	2 September 2017	245T13:13:00	1639	41.0	14.5	3.6267e-11
292	9 September 2017	252T00:09:44	1675	25.8	9.5	2.3722e-11

* Altitude defined as distance above the Saturn radius at which atmospheric pressure is equivalent to 1-bar

Final Plunge Thruster On-Time Flight Data

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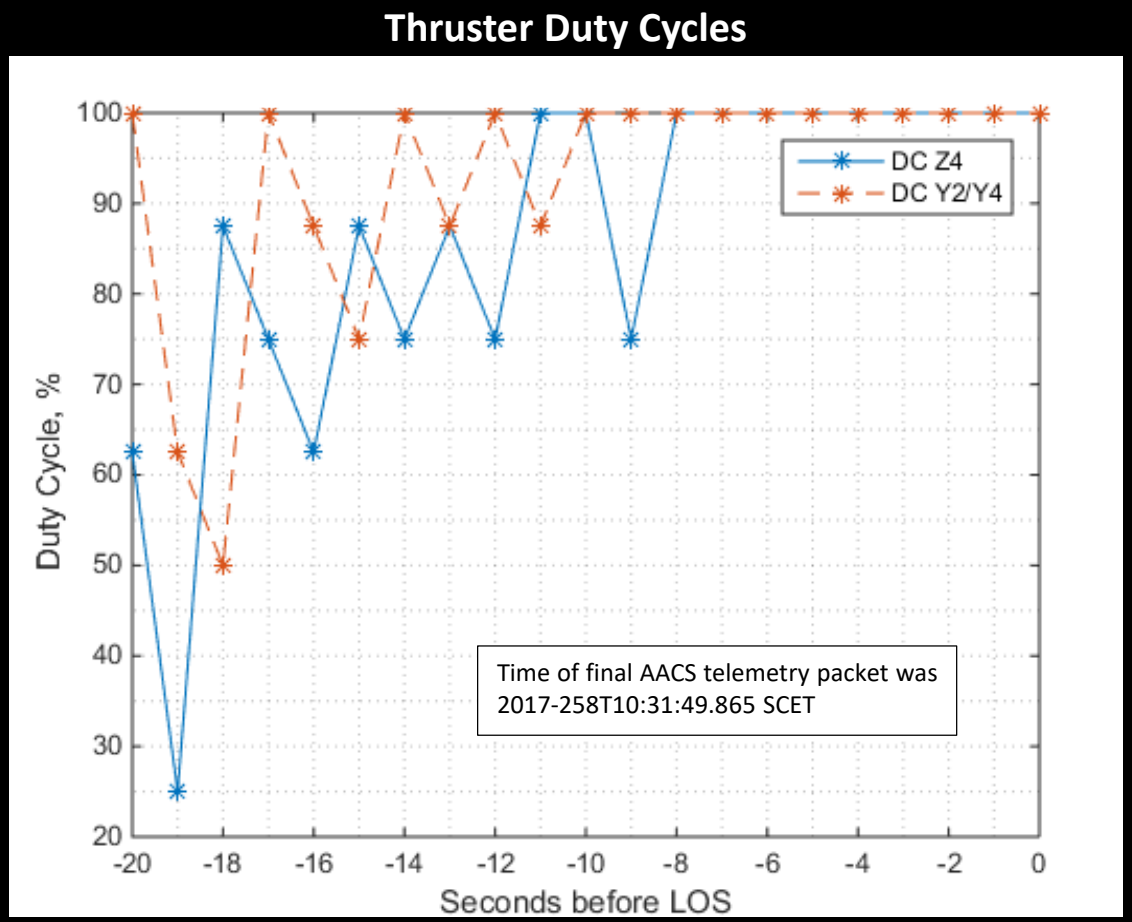
- Cassini successfully transmitted science and engineering data during plunge
- Time of final AACS telemetry packet was: 2017-258T10:31:49.865 SCET
- Z4 and Y2/Y4 thrusters reached 100% before LOS



Final Plunge Best Predicts of Density

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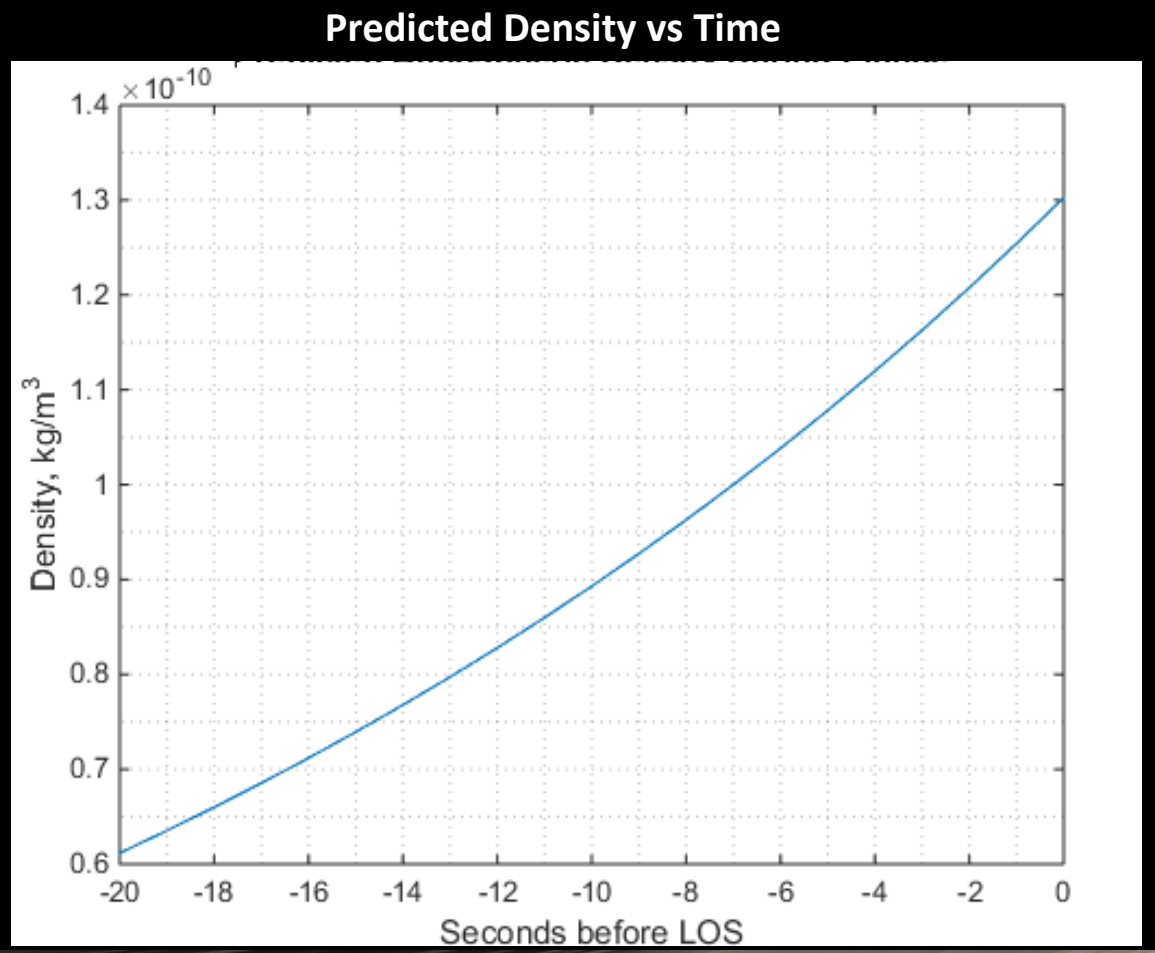
- Atmospheric measurements from Rev288-Rev292 were used to update Saturn atmosphere models, producing the following best available predicts before the plunge



Final Plunge Best Predicts of Density

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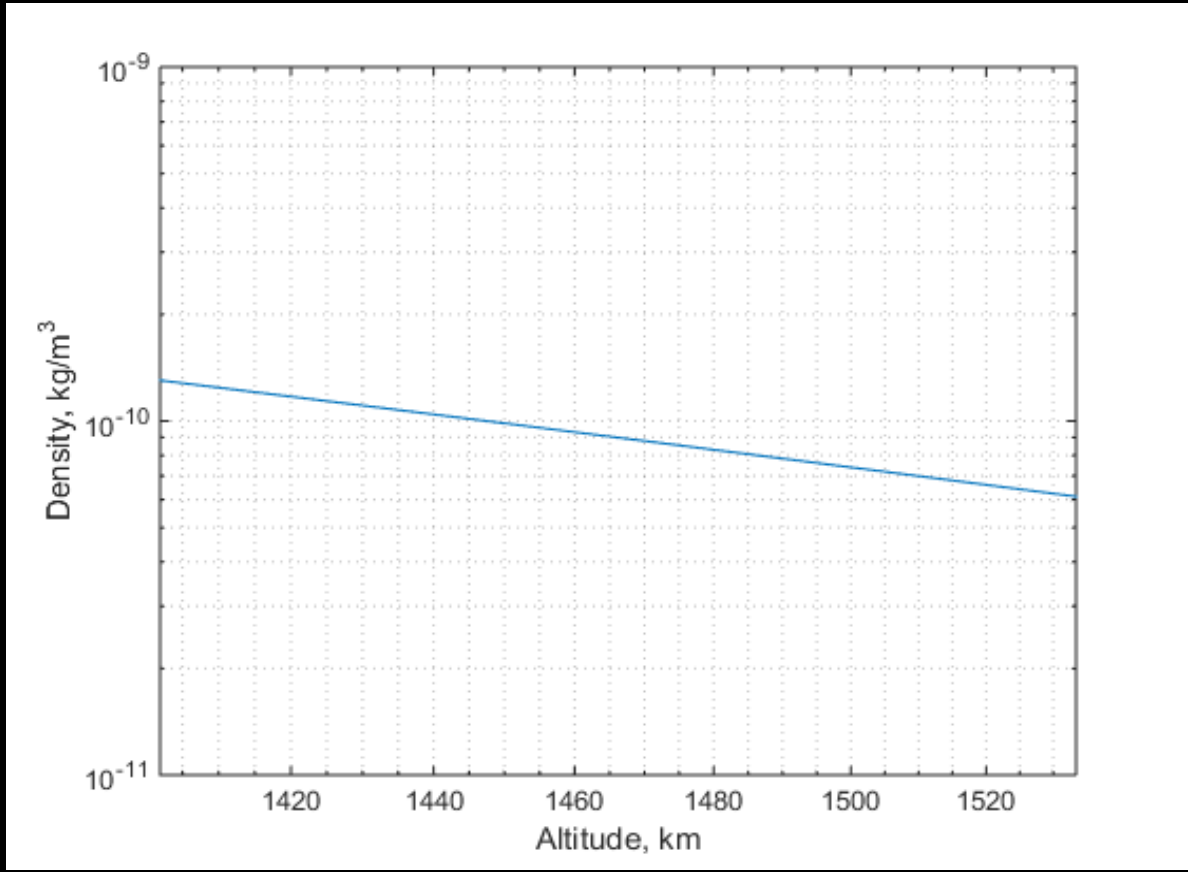
Predicted Density vs Altitude



Conclusion and Future Work

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- Thruster-based atmospheric reconstruction method was successfully applied to final five full orbits of the Cassini mission
- Informal comparisons with independent reconstruction methods validate the results in this paper
- A formal comparison will be left for future work
- The final plunge was not reconstructed in this paper
  - In order to reconstruct the final plunge, the proposed method in this paper will have to be modified
  - This will be left for future work