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A Full Mission Summary (1997-2017) of the Attitude Control Performance during Orbit Trim Maneuvers Performed by the Cassini-Huygens Spacecraft

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Cassini Overview

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Mission Timeline:

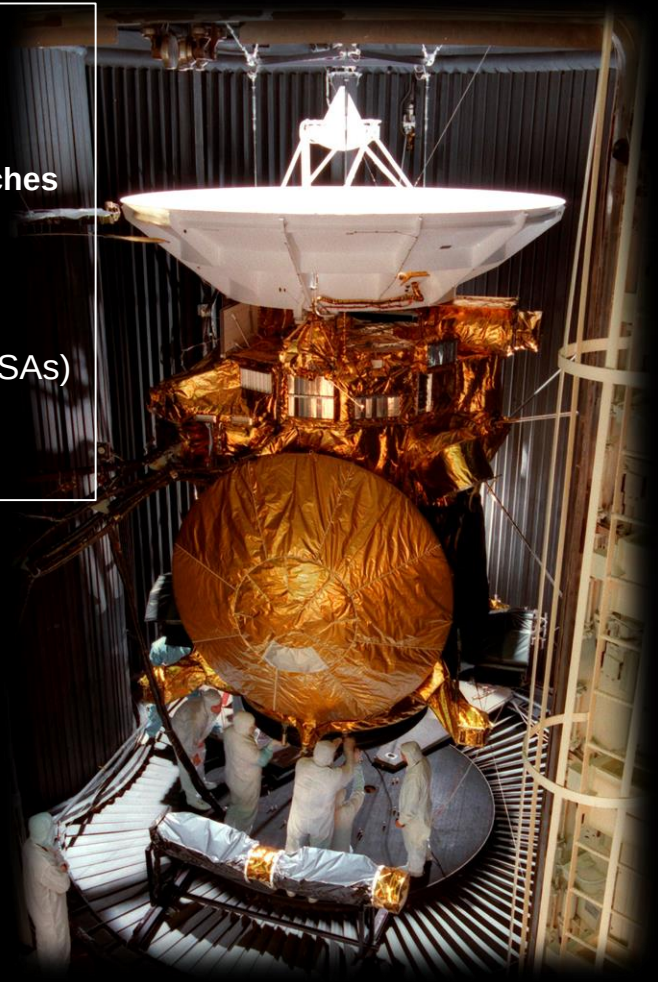
- Launch: October 1997
- Saturn Arrival: 2004
- Huygens Probe Delivery to Titan: 2005
- Prime Science Mission: 2004-2008
- Extended Mission (XM): 2008-2010
- 2nd Extended Mission (XXM): 2010-2017
- Mission End: Saturn Impact on Sept. 15, 2017

Spacecraft Description:

- Size: 6.7 m tall, 4 m wide, 11 m long MAG boom
- Mass: 5573 kg at launch (3132 kg of propellant)
- Power: 3 RTGs produce 600 W (at end of mission)
- Payload: 12 science instruments + Huygens Probe
- No scan-platform; attitude maneuvers commonplace
- Distance from Earth: ~1 Billion miles
- Round-Trip Light Time: ~3 Hours

Attitude Control Subsystem

- 3-Axis stabilized using RCS or RWA control
- 3 orthogonal 36 Nms RWAs (also 1 backup)
- **Eight 1N RCS thrusters each in 2 redundant branches**
- **2 redundant 450 N main engines**
- 1 Accelerometer (for maneuvers)
- 2 redundant ACS Flight Computers
- 2 redundant Sun Sensors Assemblies on HGA (SSAs)
- 2 redundant Stellar Reference Units (SRUs)
- 2 redundant Inertial Reference Units (IRUs)



Cassini Main Engine and Thrusters

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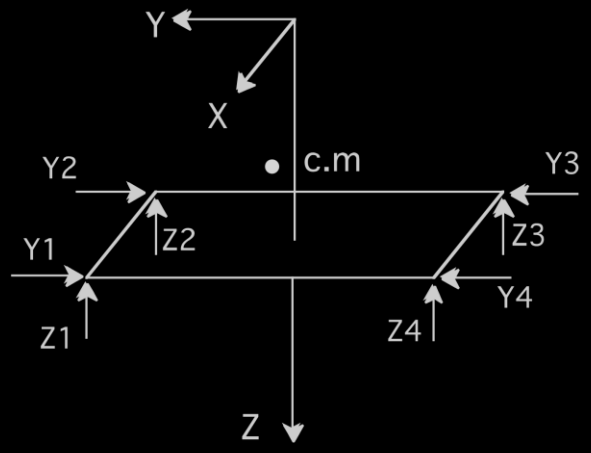
Main Engine Maneuvers

- Bipropellant MMH and NTO
- Only Main Engine-A (ME-A) was ever used
- Two axis gimbal control for Main Engines
- ME-A controlled X&Y attitude error
- Z-axis attitude error controlled with Y-facing RCS thruster couples
- Single-axis accelerometer used for cutoff
- Used for all maneuvers >300 mm/s

RCS Thruster Controlled Maneuvers

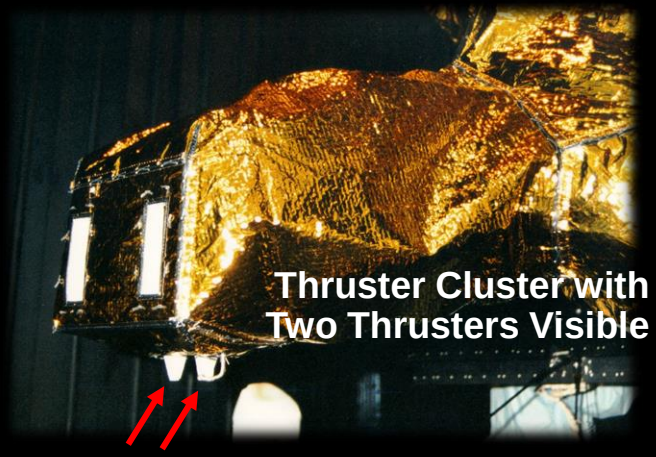
- A-Branch used from 1997-2009
- B-Branch used from 2009-2017
- All 4 Z-facing thrusters on for maneuvers
- X&Y attitude error controlled by off-pulsing
- Z-axis attitude error controlled with Y-facing RCS thruster couples
- Accumulated on-time used for cutoff (i.e. timed burns)
- Used for maneuvers 8 mm/s – 300 mm/s

RCS Thruster Configuration



1 Newton Monopropellant RCS Thruster

450 N Main Engines



Thruster Cluster with Two Thrusters Visible

Maneuver Sequence Overview

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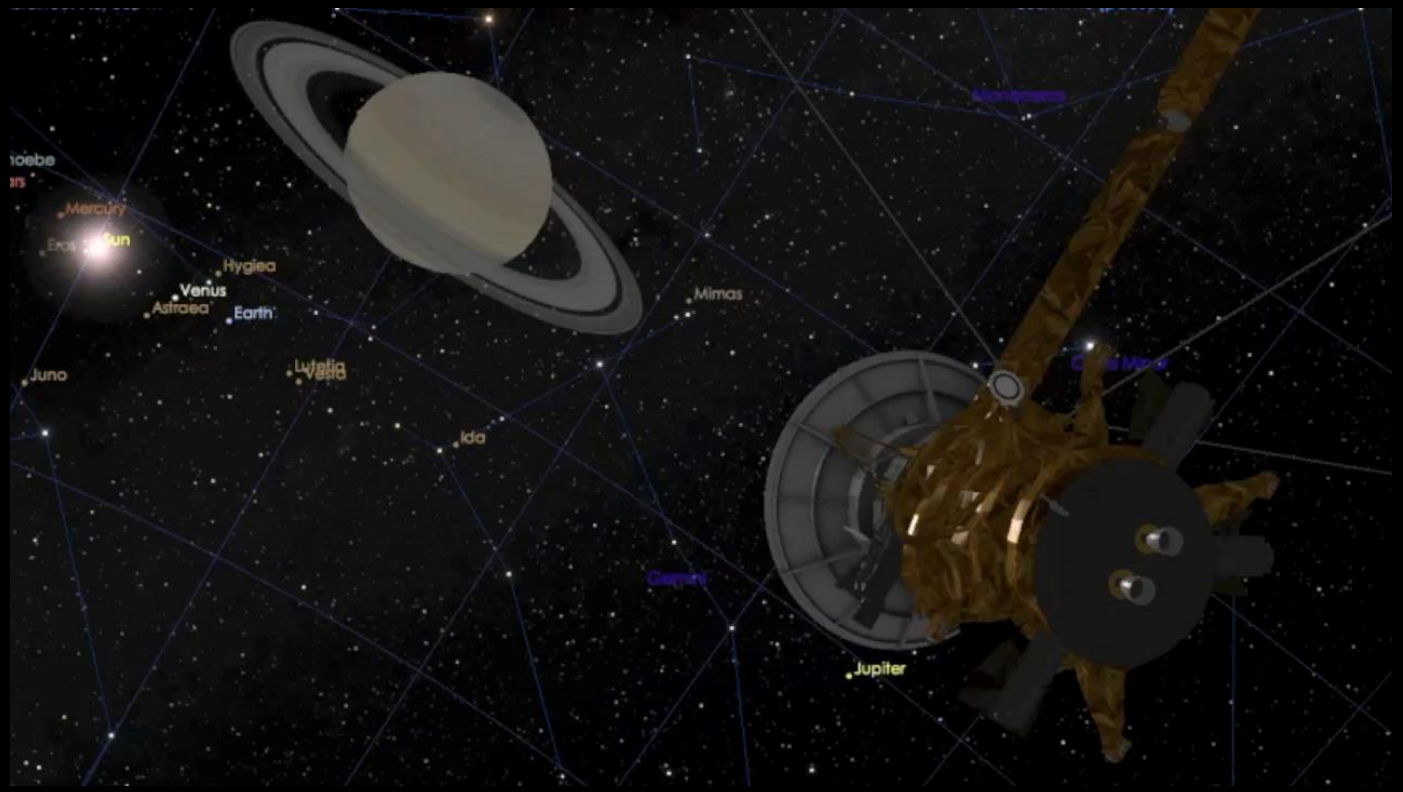
- Two-turn (roll/yaw) strategy used to get to/from burn attitude
  - For thermal constraints and boresight protection
- Accelerometer bias calibrated prior to ME maneuvers
- Settling time (for fuel slosh) at burn attitude before maneuver
- Settling time (for SC dynamics) at burn attitude after maneuver
- No communication once the spacecraft begins Yaw Turn (2nd slew) until after burn is complete and HGA repointed at Earth
- Slews on RWA control for RCS maneuvers
- Yaw slews on RCS control (with RWAs spun-down) for ME maneuvers



Cassini Maneuver Statistics

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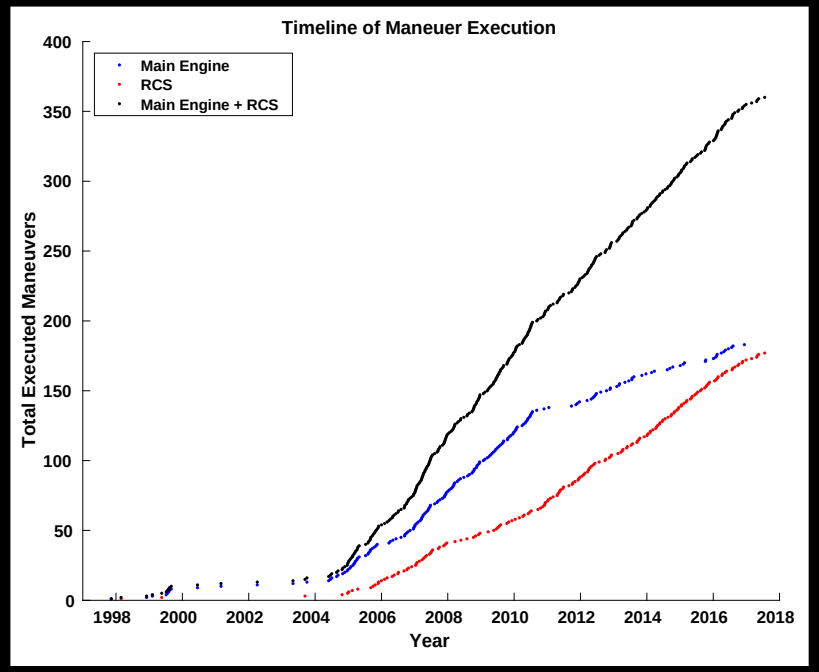
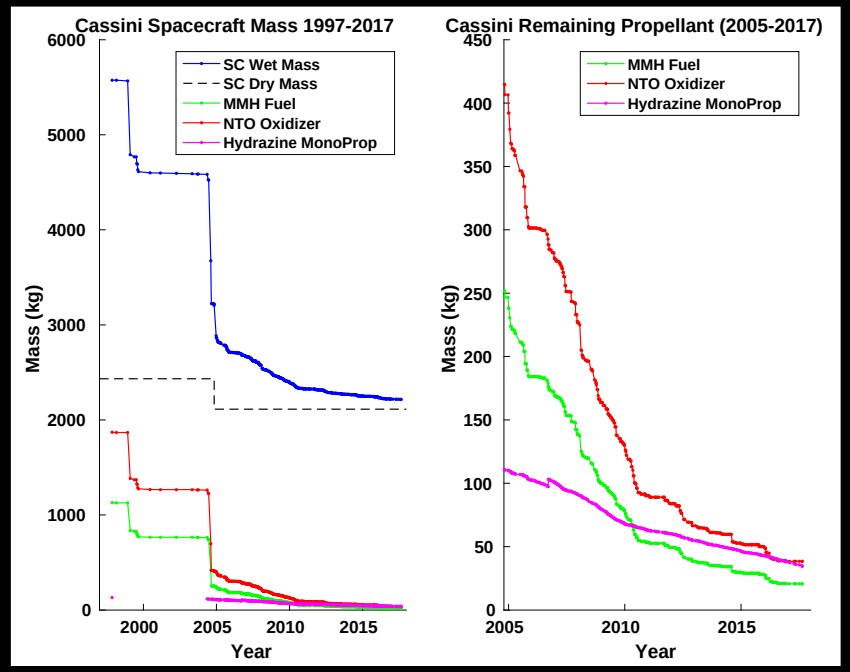
- 502 Maneuvers planned
  - Often cancelled if planned ΔV smaller than ~10 mm/s
- 360 Maneuvers executed
  - 183 ME Maneuvers
  - 177 RCS Maneuvers
- 1st maneuver 25 days into mission (1997-313)
- Final maneuver 62 days before mission end (2017-196)
- During Tour, 1 maneuver every ~4-7 days
  - Shortest gap: 3.7 days
  - Longest gap: 399 days (during Cruise)
  - Most frequent gap: 4-7 days
  - 80% of maneuvers were less than 3 weeks from previous burn



- Maneuvers infrequent during interplanetary cruise (1997-2004)
- Fewer Main Engine maneuvers during XXM (2010-2017) due to ΔV constraint on tour design



- 3000 kg of bipropellant at launch
  - ~59 kg (2%) remained at end of mission
- 132 kg monopropellant at launch
  - ~34kg (25%) remained at end of mission
  - Remaining amount was ~5 years worth
- 302 kg Huygens probe deployed to Titan's surface in January 2005

Maneuver Sizes

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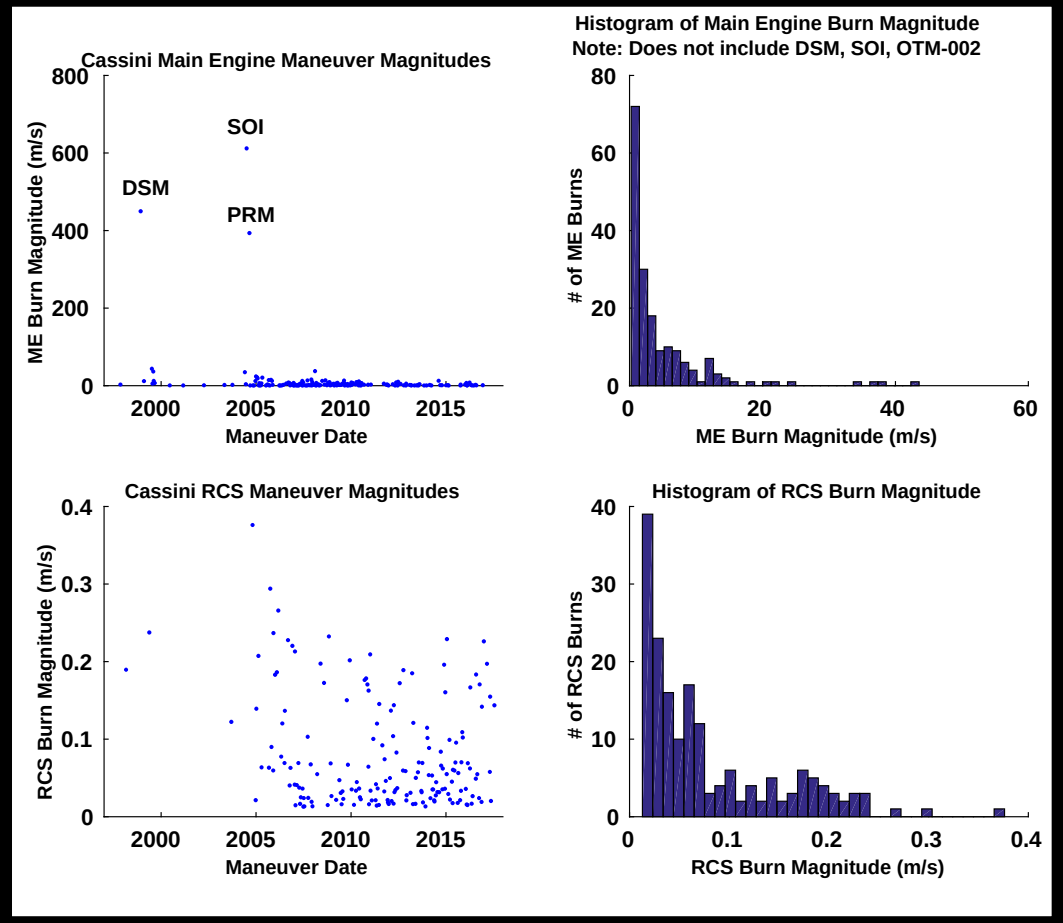
Main Engine Maneuvers

- Largest: 626.17 m/s (Saturn Orbit Insertion)
- Three maneuvers (SOI, DSM, and PRM) consumed 69% of the 3000kg of bipropellant
- 68% of the 183 ME maneuvers less than 5 m/s
- >10 m/s was approximate level that Operations team considered to be a “large” maneuver

RCS Maneuvers

- Smallest: 8.3 mm/s
  - AACS FSW capable of smaller maneuvers, but Ops Constraints precluded them
- 66% of RCS maneuvers less than 80 mm/s



RCS Maneuver Duty Cycles

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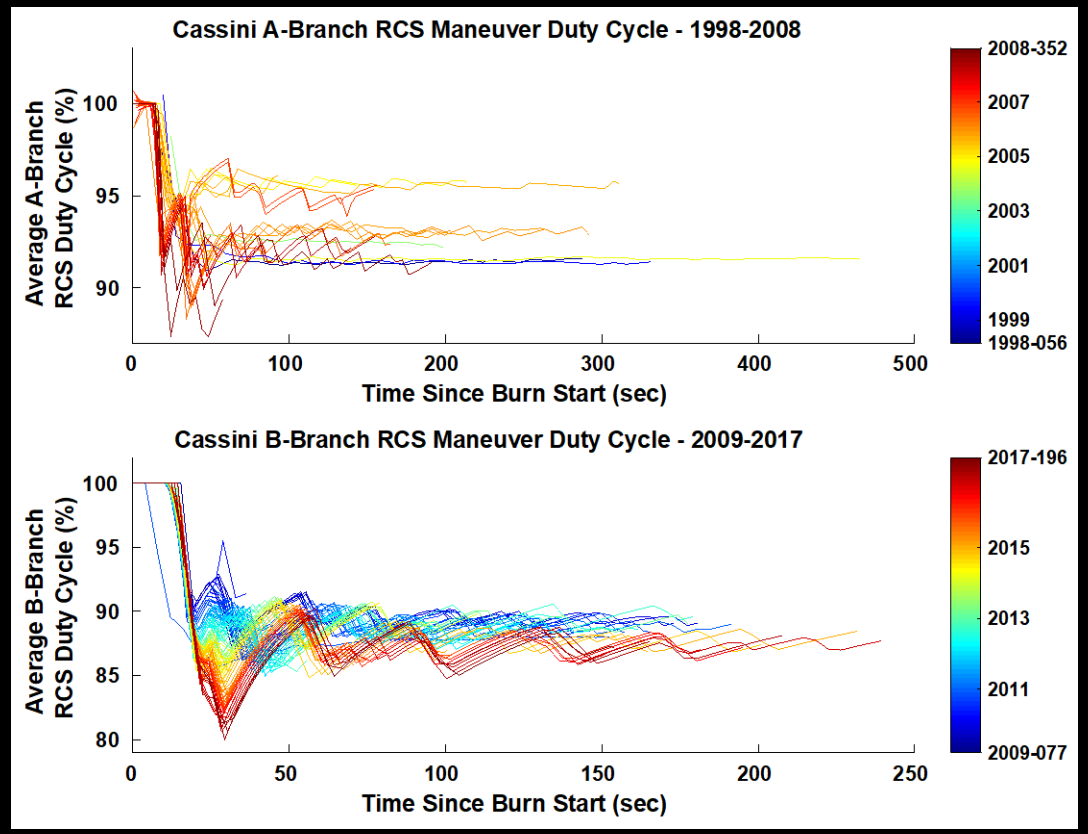
- $Duty\ Cycle\ (\%) = \frac{(Accumulated\ RCS\ On\text{–}Time)}{(Elapsed\ Burn\ Time)} \times 100\%$
- Duty Cycle shown is average for the 4 Z-facing thrusters
  - Duty Cycle for individual thrusters computed also
- Duty Cycle lower than 100% for RCS maneuvers due to off-pulsing for X & Y axis control
  - CM offset caused variable RCS lever arms
- RCS Duty Cycle closely monitored for early signs of thruster degradation
  - Anomalous thrust degradation of 2 A-Branch thrusters prompted swap to backup thruster branch
- Gradual duty cycle evolution consistent with gradually shifting CM location



ME Maneuver Gimbal Pointing

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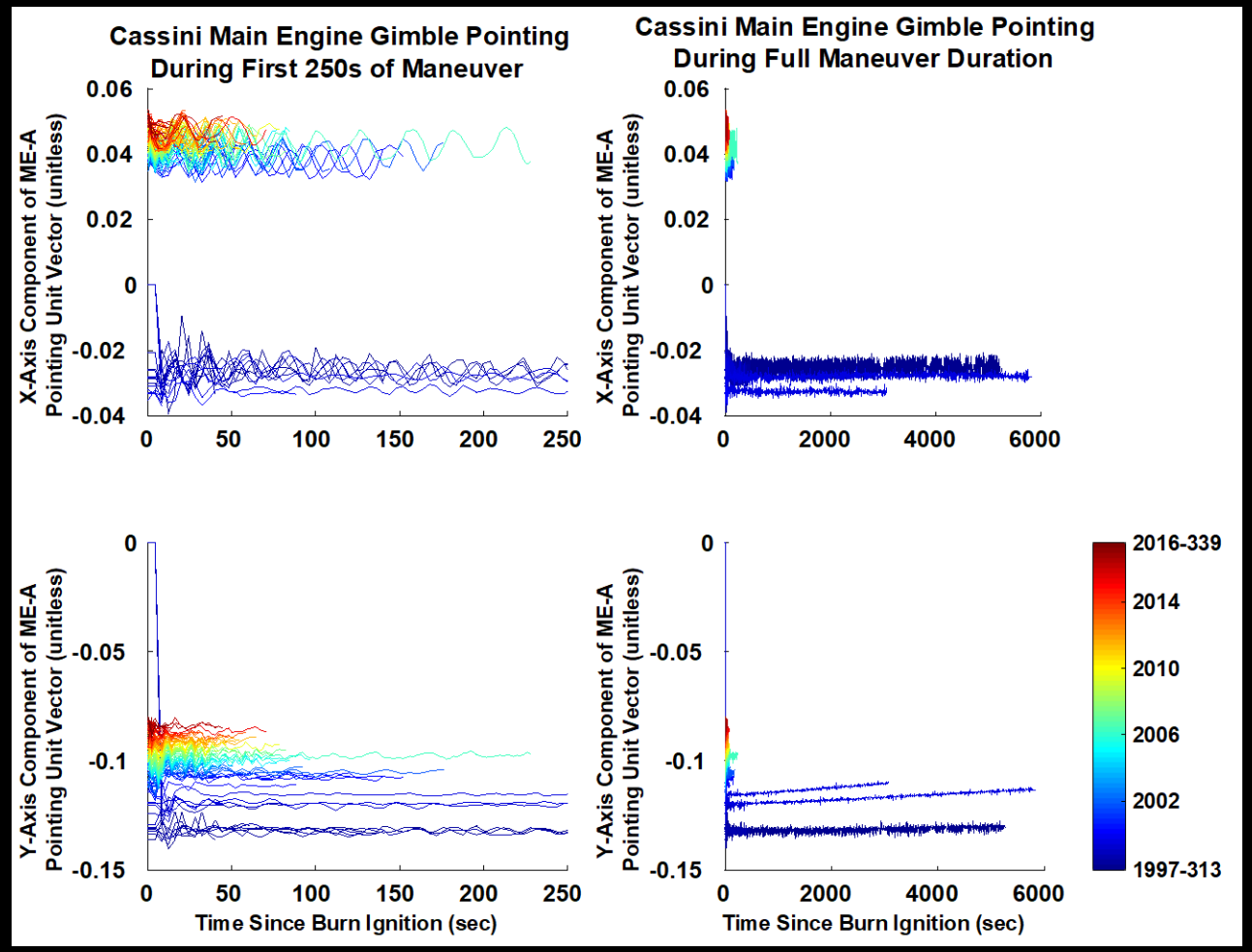
- Two-axis gimbal on Main Engine "preaimed" at estimated CM location prior to each maneuver
  - Telemetry from maneuvers used to update "preaim" location for next maneuver
- Long term changes in ME pointing direction due to mass properties changes
  - ME gimbal effectively pointed ME-A nozzle at CM location to achieve X & Y axis control
- Change in CM location visible during the 3 largest ME maneuvers
  - CM motion due to propellant mass depletion



ME Engine Preaim Vector

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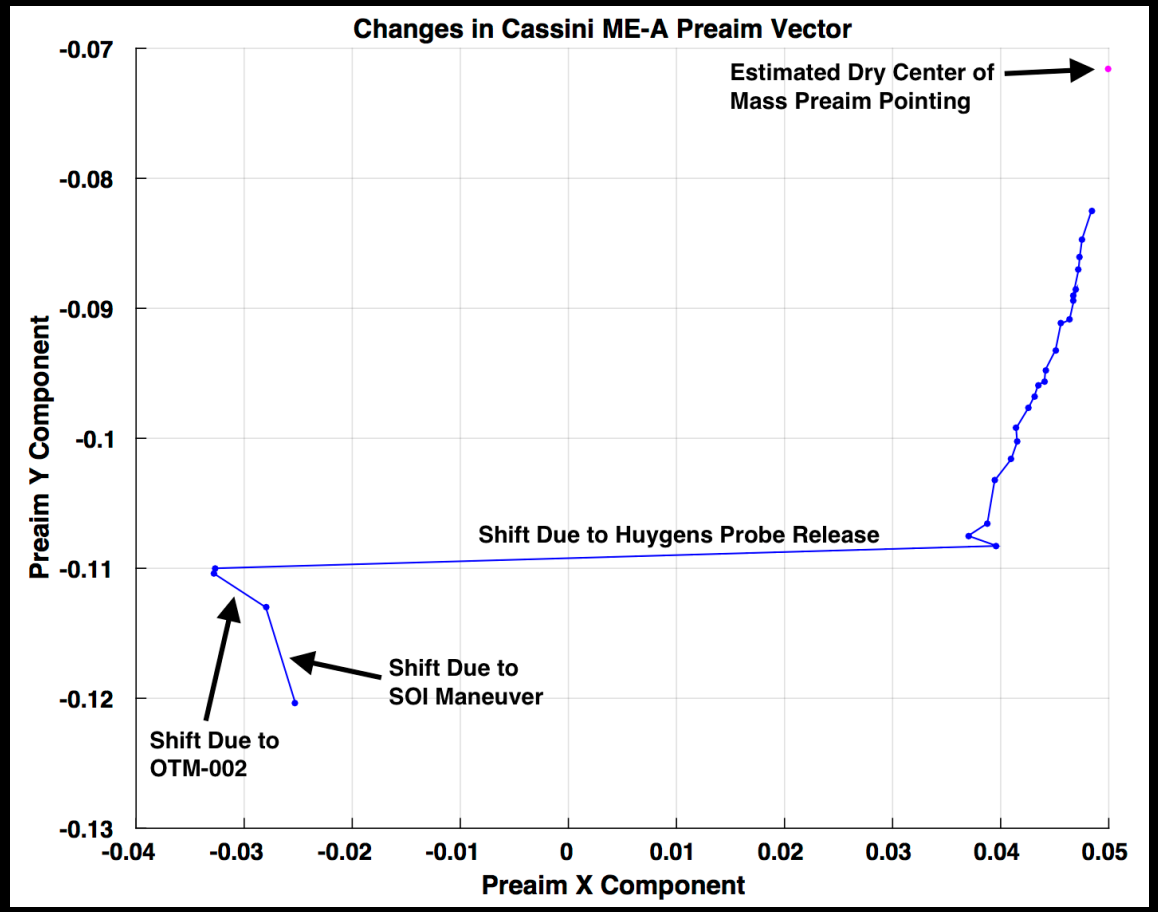
- Two-axis gimbal on Main Engine "preaimed" at estimated CM location prior to each maneuver
- Preaim direction gradually shifted due to mass properties changes
- Huygens probe release resulted in large preaim shift
  - CM shifted from –X to +X side of YZ plane
- After Huygens release, preaim moved in a predictable manner for remainder of mission



Maneuver Execution Errors

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- JPL uses "Gates Model" to compute execution error in terms of:
  - Magnitude Error – Parallel to direction of intended maneuver
  - Pointing Error – Perpendicular to direction of intended maneuver
- JPL spacecraft are designed to achieve maneuver accuracy requirements
- Execution Error requirements make allowances for:
  - Fixed error (i.e. a bias/noise term)
  - Proportional error (i.e. scale factor term)
- Pre-launch execution requirements can be used for benchmarks of true in-flight performance

	Main Engine Maneuver		RCS Thruster Maneuver	
1σ Requirement	Proportional	Fixed	Proportional	Fixed
Magnitude Error	0.2%	10 mm/s	2.0%	3.5 mm/s
Pointing Error	3.5 mrad	17.5 mm/s	12.0 mrad	3.5 mm/s

$$\bar{e}_{Magnitude} = \bar{V}_C - (\bar{V}_A \cdot \bar{v}_C)\bar{v}_C$$

$$\bar{e}_{Pointing} = \bar{V}_A - (\bar{V}_A \cdot \bar{v}_C)\bar{v}_C$$

ME Maneuver Execution Errors

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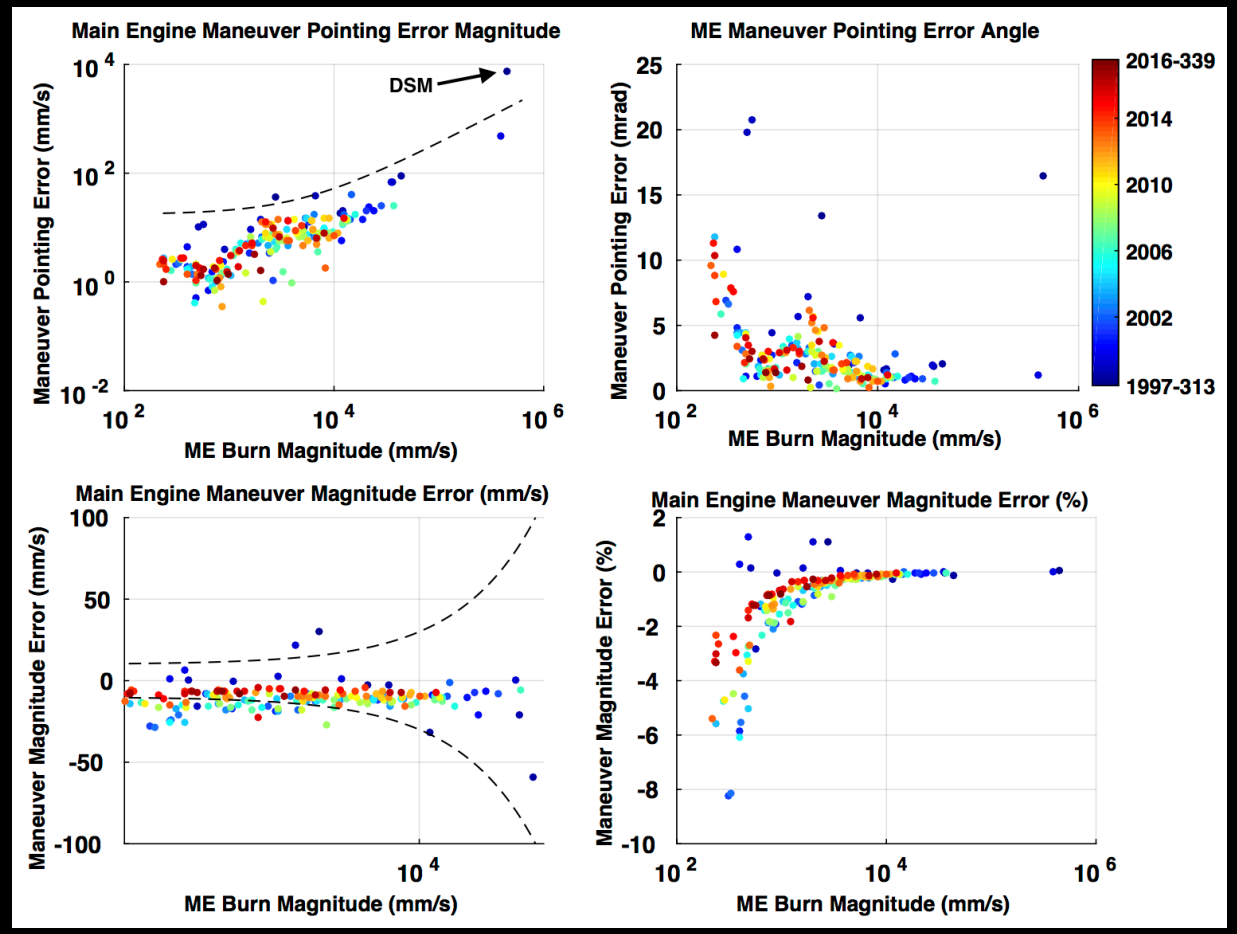
- Execution error shown in figure computed from AACS telemetry
  - "True" magnitude error determined by NAV Doppler data (not included) and showed excellent magnitude error performance (less than 1σ)
  - **Apparent "under burns" in AACS telemetry are artificial**
    - Due to FSW idiosyncrasy that under-reported post-burn thrust tail-off
- Pointing accuracy met 1σ Reqt. once system was calibrated
- Large pointing error for DSM resulted from mechanical misalignment of engine mounting
  - Corrected with commanded 15.7 mrad burn direction offset



RCS Maneuver Execution Errors

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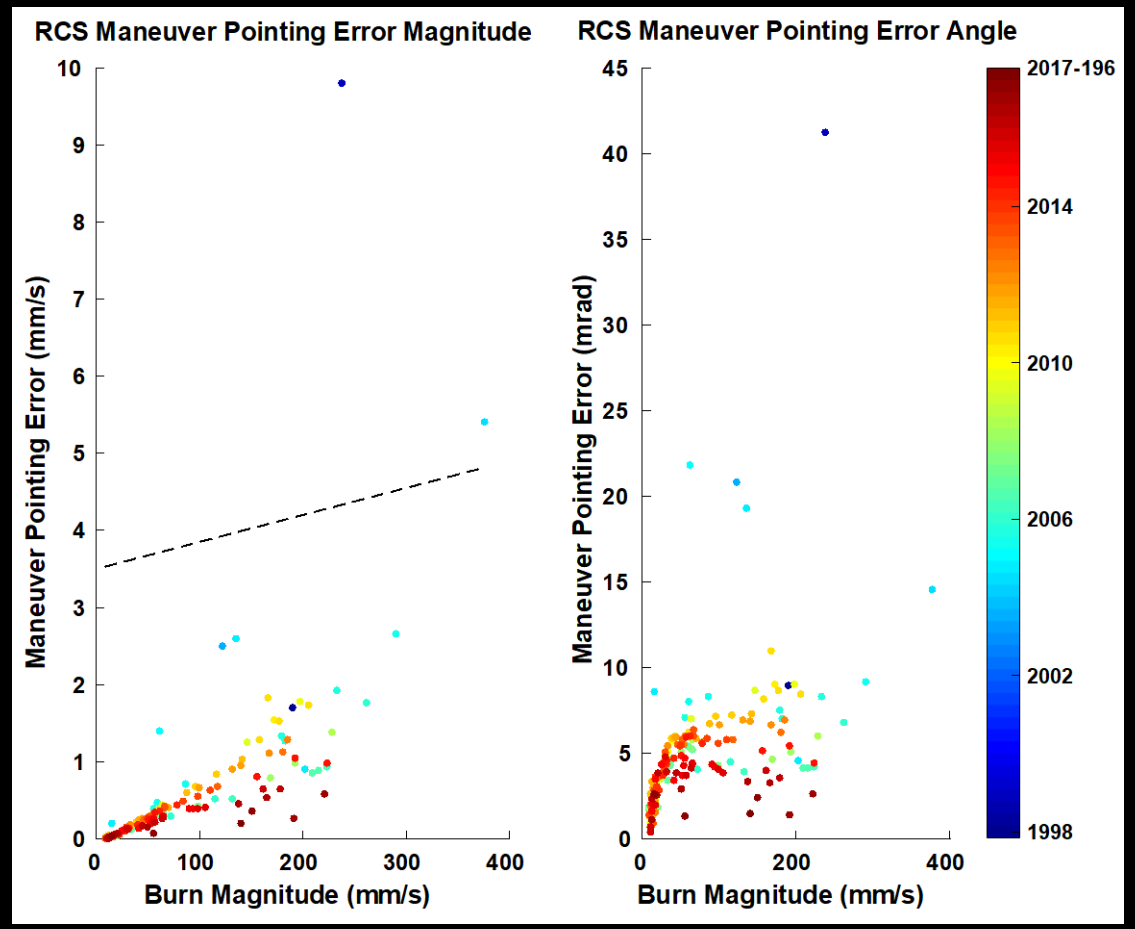
- RCS maneuver pointing accuracy easily met 1σ requirement bound for calibrated system
- Clear improvement in maneuver pointing error as mission progressed
- AACS subsystem never uses AACS telemetry to report RCS burn *magnitude* error
  - RCS burns effectively “timed burns”, so AACS TLM would show zero error
  - No independent sensor of RCS burn acceleration
    - RCS thruster force too small for accelerometer use



RCS Maneuver Attitude Error

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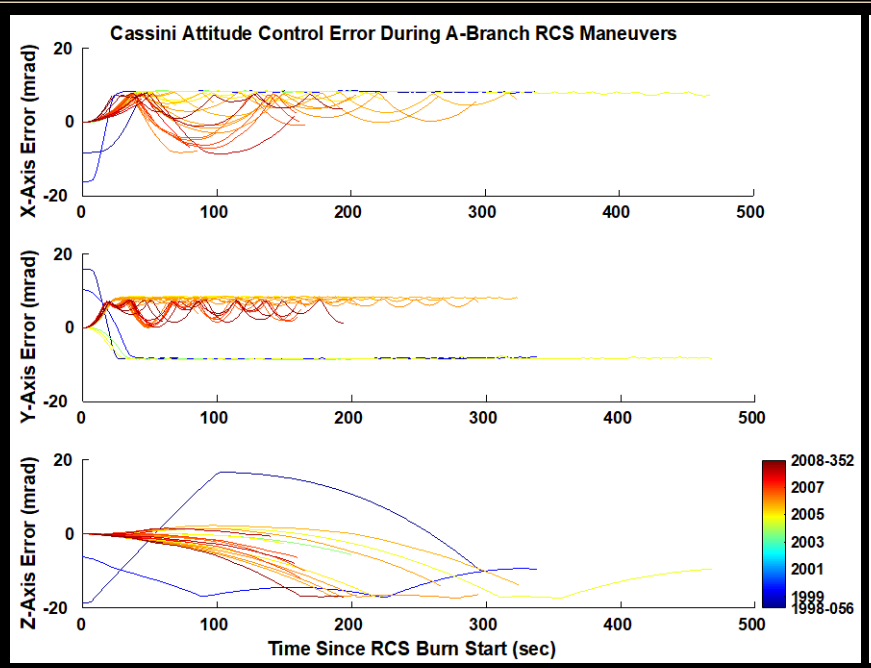
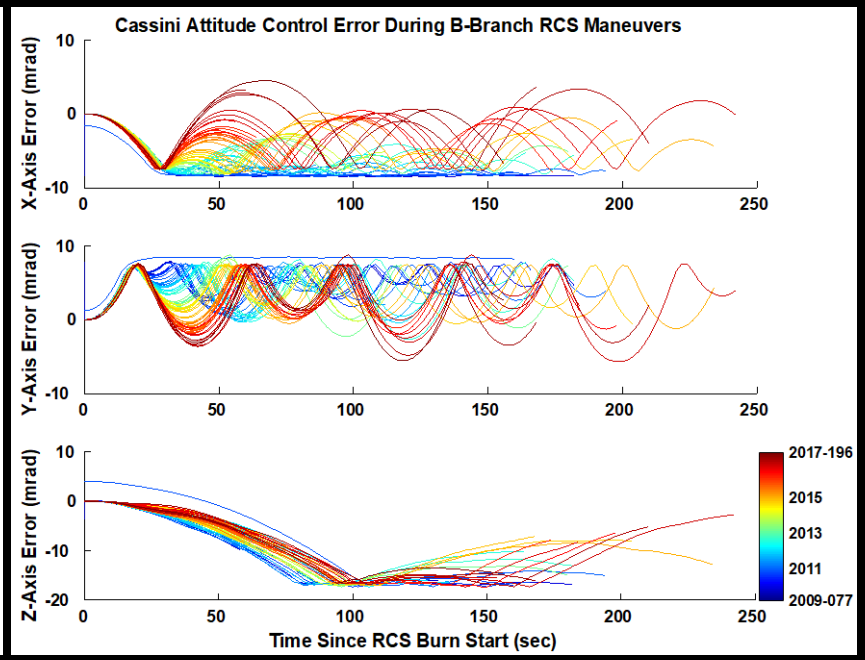
- During maneuvers, RCS position error deadband set to 8.7 mrad for X & Y and 17.5 mrad for Z-axis
- ΔV controller included an attitude integrator/summer
  - Maintained memory of prior maneuvers
  - Gradually pushed X&Y attitude error back towards zero line to decrease average pointing error





- A-branch pointing error shows polarity changes in position error due to large mass changes
  - (e.g. SOI burn, Huygens probe release)
- B-Branch pointing error shows clear repeatability and gradual evolution due to CM shifts associated with gradual propellant depletion

Cassini Maneuver Data & Conclusions

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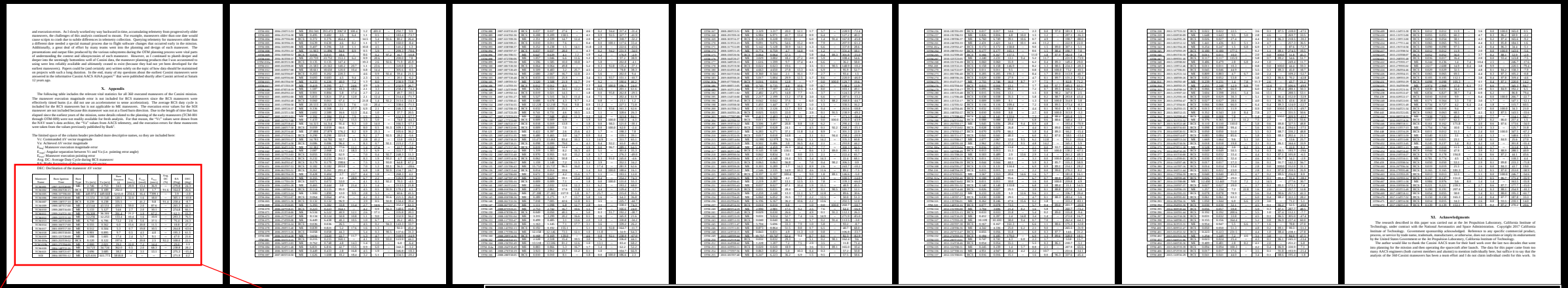

Maneuver Name	Burn Ignition Time	Burn Type	Vc (m/s)	Va (m/s)	Burn Duration (s)	E_{Mag} (mm/s)	E_{Angle} (mrad)	E_{Point} (mm/s)	Avg. DC (%)	RA (Deg)	DEC (deg)
TCM-001	1997-313T20:00	ME	2.746	2.753	34.5	29.9	13.4	36.9	--	279.8	24.3
TCM-002	1998-056T20:15	RCS	0.185	0.189	292.0	--	8.9	1.7	91.6	164.0	26.6
TCM-005	1998-337T06:00	ME	449.974	449.668	5255.0	256.6	16.4	7399.1	--	3.9	-2.8
TCM-006	1999-035T20:00	ME	11.551	11.545	120.1	32.0	1.6	18.0	--	305.1	-10.8
TCM-007	1999-138T17:10	RCS	0.239	0.238	335.5	--	41.2	9.8	91.4	258.4	-8.7
TCM-009	1999-187T17:00	ME	43.544	43.551	459.5	59.0	2.0	87.6	--	265.3	44.1
TCM-010	1999-200T16:00	ME	5.133	5.127	54.6	2.7	2.0	10.1	--	274.8	66.1
TCM-011	1999-214T21:30	ME	36.309	36.301	391.4	21.2	1.9	67.2	--	62.3	15.3
TCM-012	1999-223T15:30	ME	12.256	12.253	133.4	10.4	1.6	19.9	--	293.3	76.5
TCM-013	1999-243T16:00	ME	6.710	6.706	72.2	2.6	5.6	37.5	--	76.4	24.3
TCM-014	2000-166T17:00	ME	0.555	0.562	6.0	15.6	20.8	11.5	--	18.8	47.2
TCM-017	2001-059T17:30	ME	0.512	0.504	5.3	0.7	19.8	10.5	--	264.8	-63.6
TCM-018	2002-093T18:00	ME	0.901	0.895	9.7	0.5	4.5	4.0	--	195.3	61.5
TCM-019	2003-121T20:00	ME	1.598	1.601	17.4	2.4	5.7	9.1	--	47.0	21.6
TCM-019a	2003-253T19:52	RCS	0.120	0.122	197.6	--	20.8	2.5	92.2	108.0	22.1
TCM-019b	2003-275T04:00	ME	2.000	2.021	39.3	22.0	7.2	14.4	--	29.0	3.3
TCM-020	2004-148T22:26	ME	34.723	34.724	362.0	0.5	2.0	68.3	--	238.8	28.2
TCM-021	2004-168T21:07	ME	3.696	3.685	38.3	1.2	3.5	13.1	--	275.3	-15.4
SOI	2004-183T01:12	ME	625.616	611.773	5818.8	--	--	--	--	271.9	4.2

- Conference paper includes long table of Maneuver Performance data
  - Includes all maneuvers that Cassini executed in 20 years of flight
- The paper captures for posterity:
  - Basic statistics about maneuver size, separation, type
  - Analysis of execution errors and pointing accuracy
  - Figures that show AACS behaviors during maneuvers
- In Conclusion:
  - Cassini's 360 successful maneuvers across 20 years of flight are a testament to the fusion of a well designed ΔV controller in FSW and a well developed ground operations process to execute the maneuver
  - Maneuver execution process was continually updated to improve performance and to guard against errors

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