Jet Propulsion Laboratory
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Cassini Maneuver Performance Assessment and Execution-Error Modeling Through 2015

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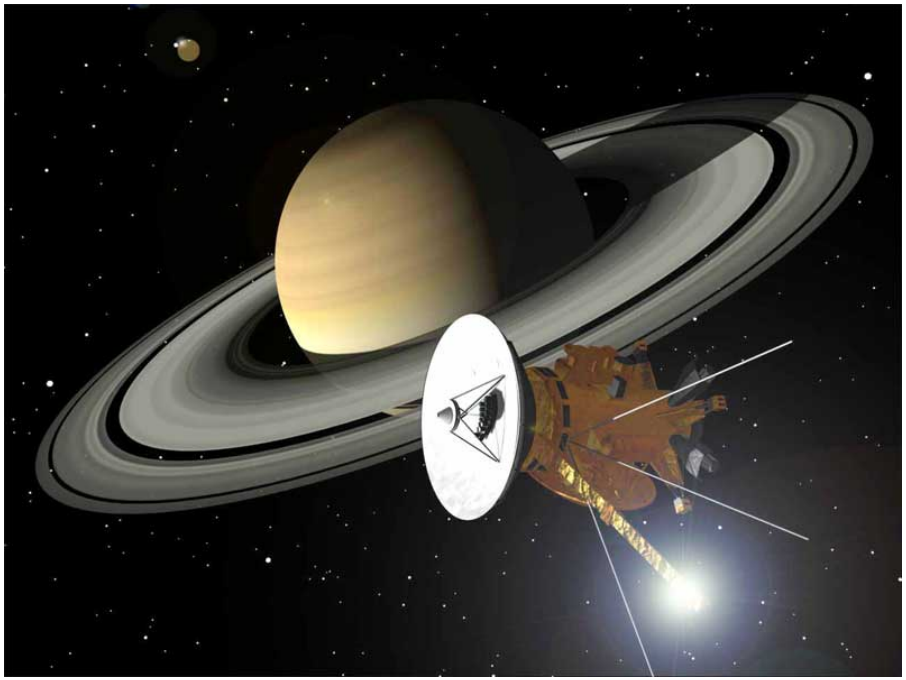
Cassini Mission at Saturn and Titan

The Cassini-Huygens spacecraft launched on October 15, 1997. After a seven-year cruise, it arrived at Saturn on July 1, 2004 and began a four-year Prime Mission to study the Saturnian system.

Two extended missions followed: the two-year Equinox Mission starting in September 2008 and the seven-year Solstice Mission which began in September 2010.



As of February 8, 2016, Cassini has executed a total of 333 maneuvers:

- 175 maneuvers via bi-propellant main engine assembly (MEA)
- 158 maneuvers via Reaction Control System (RCS) thrusters
- 30+ maneuvers are planned from now through end of mission in September 2017

Overview

- Paper presents a recent analysis of maneuvers executed by Cassini with main engine and RCS through December 30, 2015 and validates current execution-error models in use since August 2012
- Three MEA execution-error model recommendations are discussed:
  - Two models for all main engine maneuvers (one with biases remaining and one with biases removed)
  - One model limited to burns under 5 m/s
- Three RCS model recommendations are also highlighted:
  - Two models for RCS burns performed on B-branch (one with biases remaining and one with biases extracted)
  - One 'mixed-branch' model for RCS burns executed using thrusters from both A and B branches
- Follow-up to the following manuscripts:
  - AAS 08-113: "Execution-Error Modeling and Analysis of the Cassini-Huygens Spacecraft Through 2007"
  - AAS 14-390: "Maneuver Performance Assessment of the Cassini Spacecraft Through Execution-Error Modeling and Analysis"

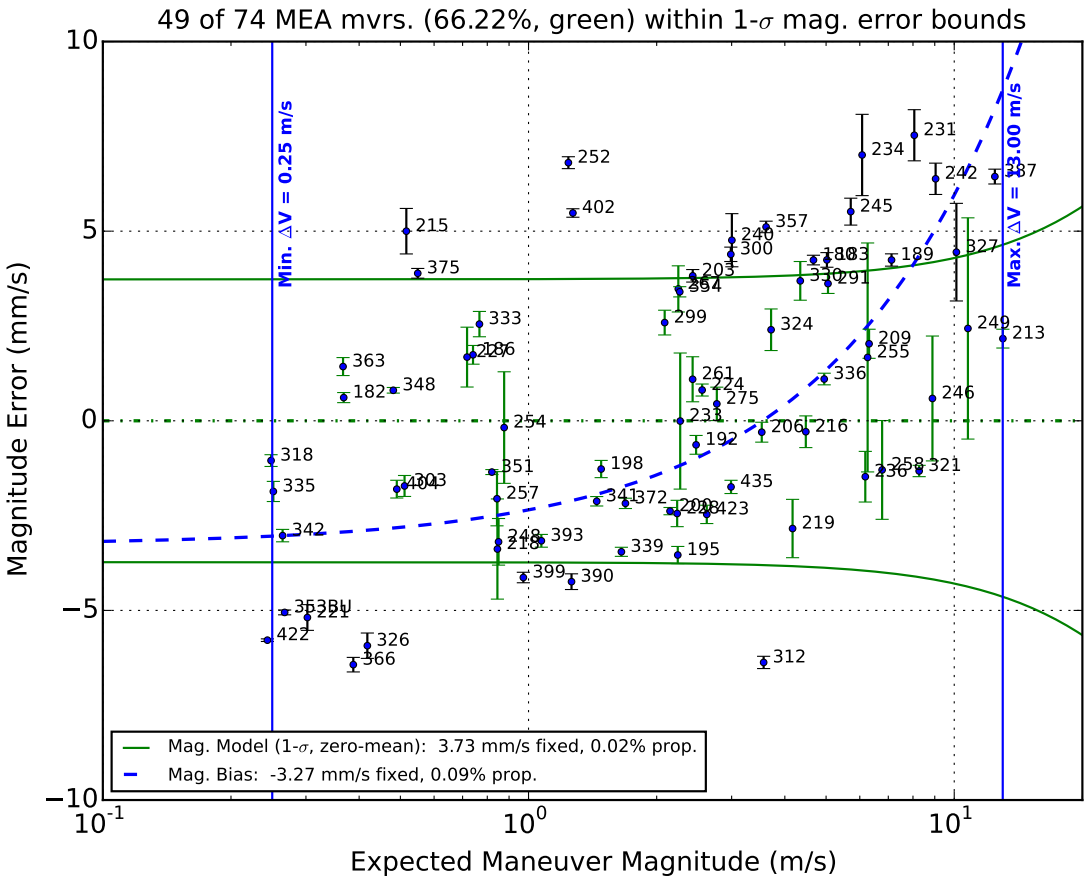
Current Models for Cassini Execution Errors

2012-1 Execution-Error Models (1-σ). *In use since August 2012*

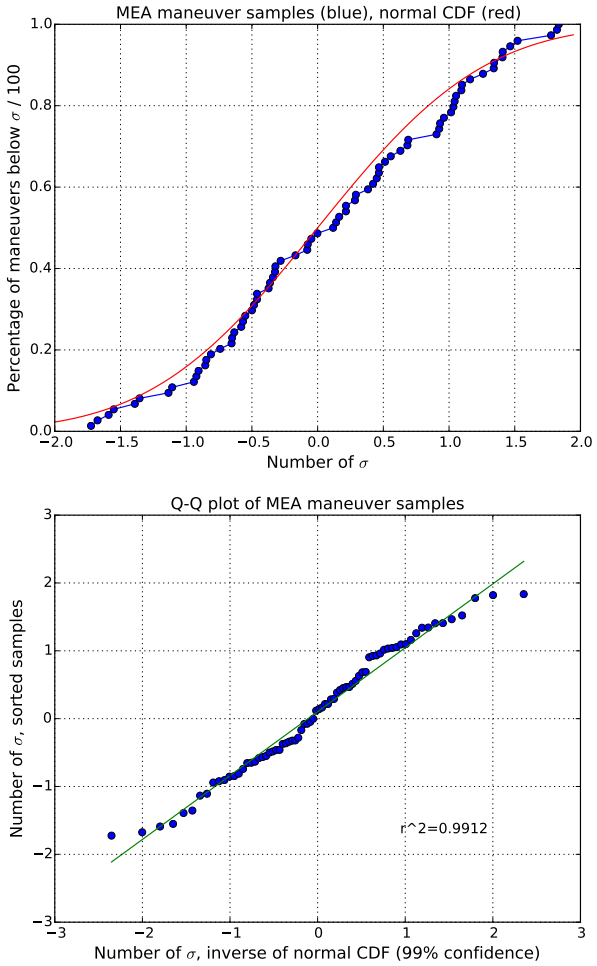
		Main Engine ($\leq$ *13 m/s*)	RCS ($\leq$ *0.3 m/s*)
Magnitude	Proportional (%)	0.02	0.4
	Fixed (mm/s)	3.5	0.5
Pointing (per axis)	Proportional (mrad)	1.0	4.5
	Fixed (mm/s)	5.0	0

- Maneuver execution errors are represented via the Gates model
  - Fixed and prop-magnitude errors, and fixed and prop-pointing errors
  - Maximum-likelihood estimation to compute Gates-model parameters
- MEA model represents errors seen w/ 48 MEA burns after fuel-side repressurization in Jan. 2009 thru June 2012 (OTMs 180–326)
  - -4 mm/s fixed-magnitude bias removed via flight software patch
- RCS model represents errors seen w/ 49 RCS maneuvers following March 2009 thruster branch swap thru July 2012 (OTMs 183x–328)
  - Prop-mag bias removed via -1.5% change to RCS thrust adj. factor
  - Fixed-mag bias taken out by adding 0.8 mm/s to deadbanding ΔV

Main Engine Magnitude Errors (2016-1L Model)



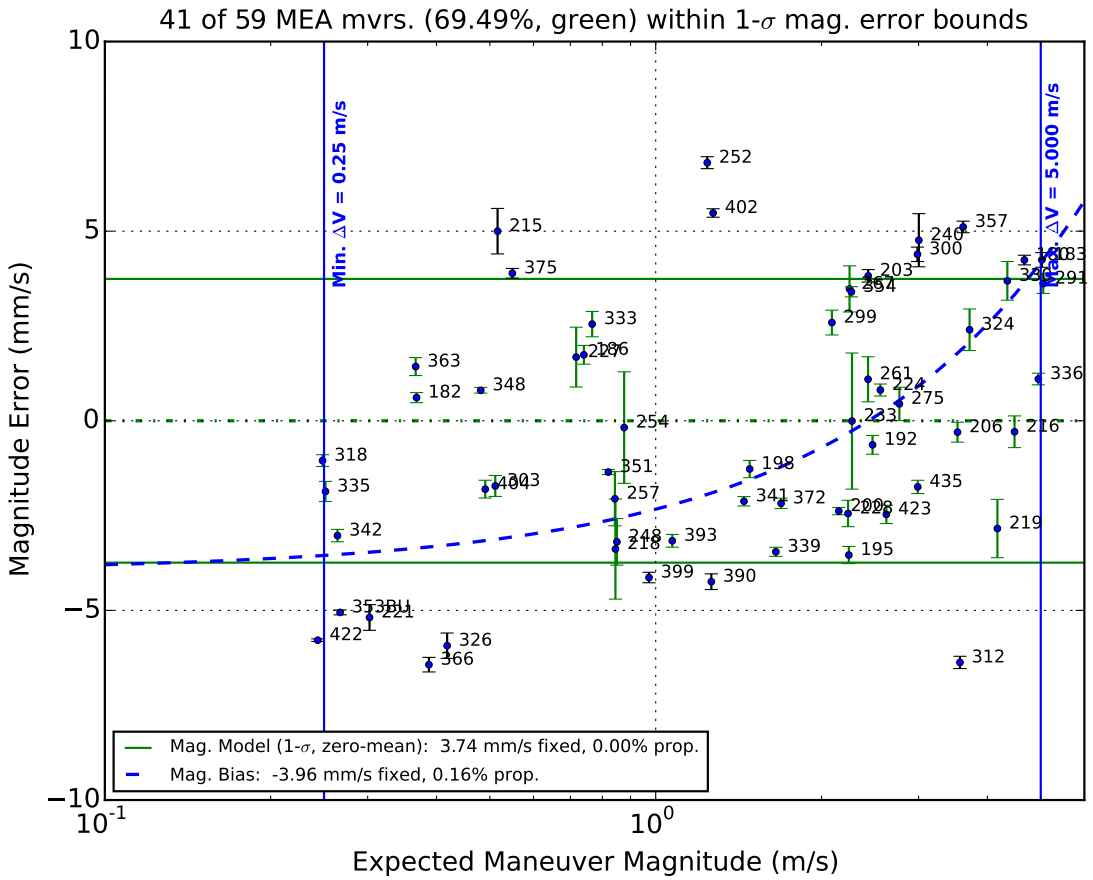
Magnitude Errors (Zero-Mean Model)



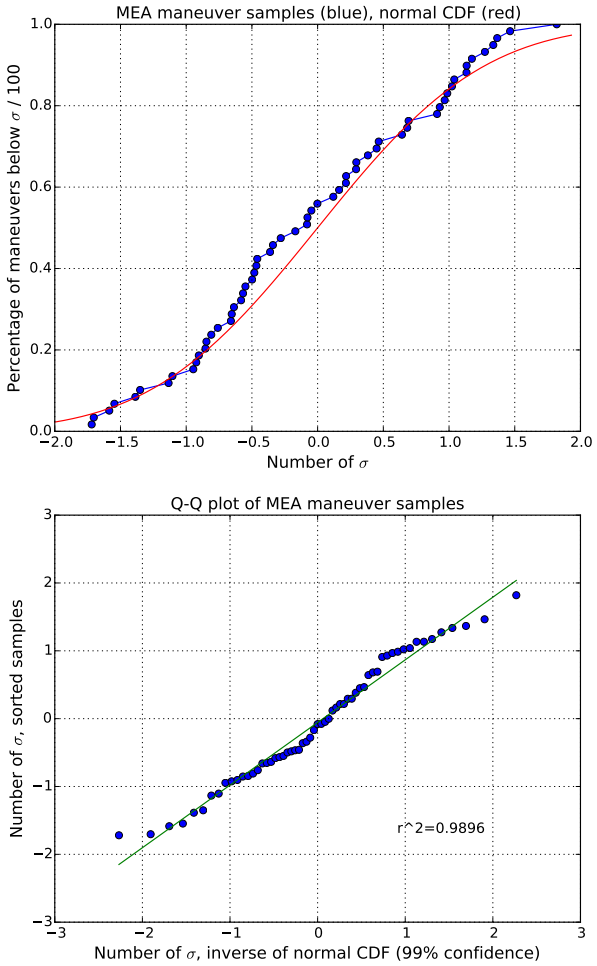
Mag-Error CDF & Q-Q Plots

2016-1L Main Engine Execution-Error Model (OTMs 180–435 Main Engine Burns). *Model assumes no bias in data and is valid for MEA burns $\leq$ 13 m/s.*

Main Engine Magnitude Errors (2016-1S Model)



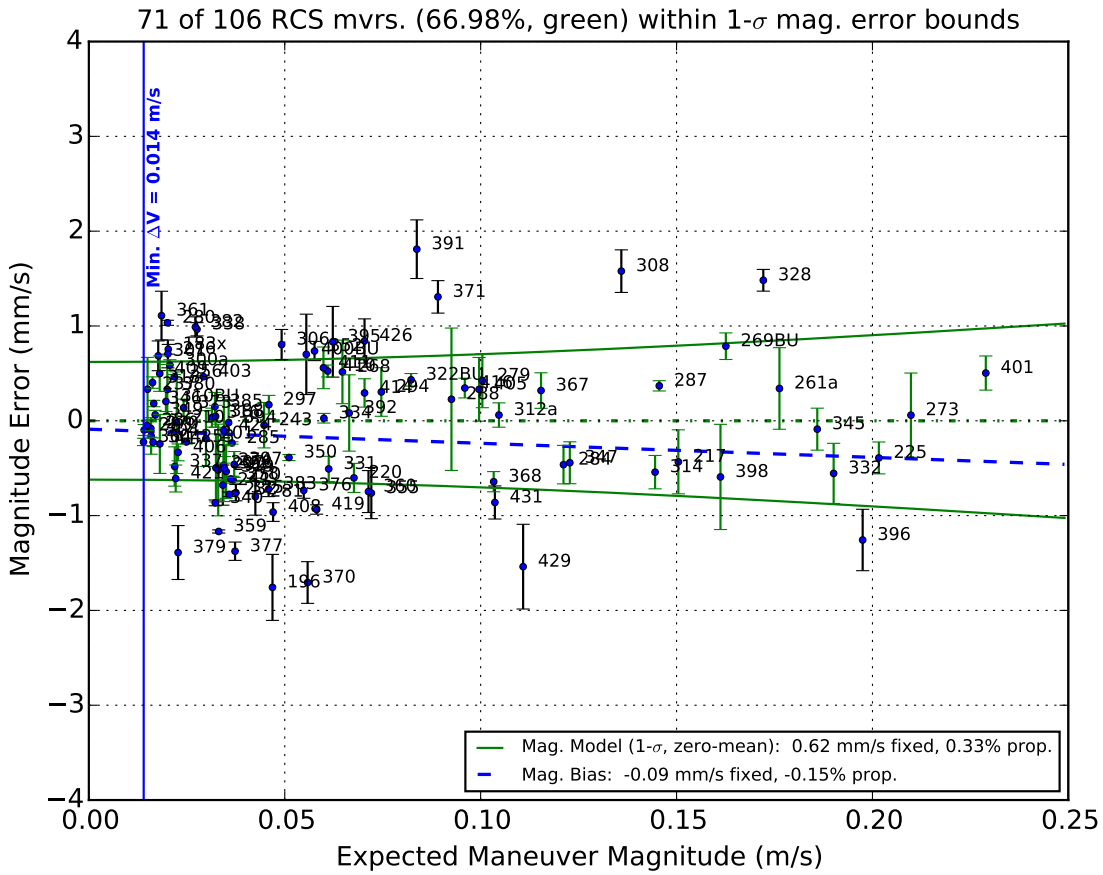
Magnitude Errors (Zero-Mean Model)



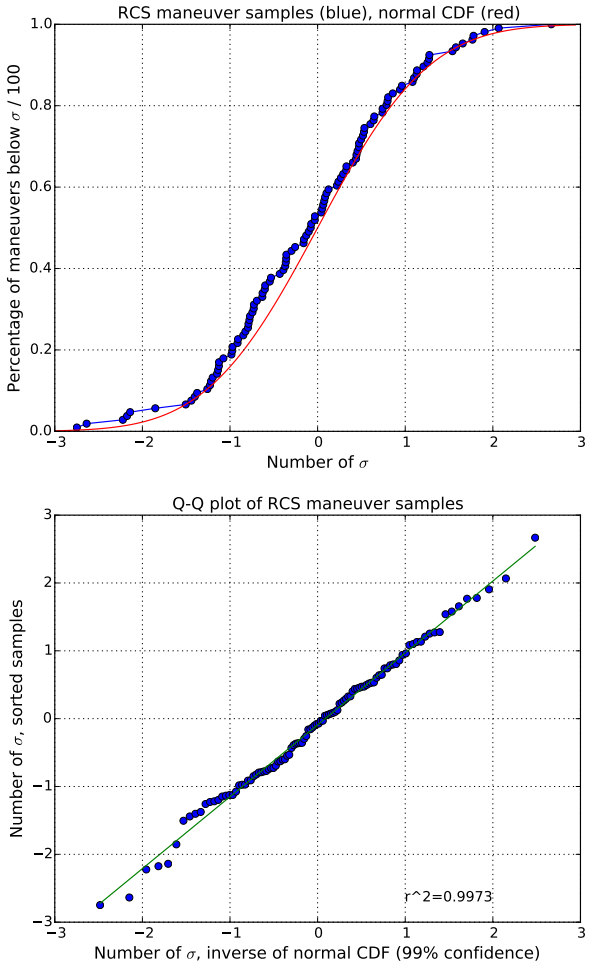
Mag-Error CDF & Q-Q Plots

2016-1S Main Engine Execution-Error Model (OTMs 180–435 MEA Burns $\leq$ 5 m/s). *Model assumes no bias in data and is valid for MEA burns $\leq$ 5 m/s.*

RCS Magnitude Errors (2016-1B Model)



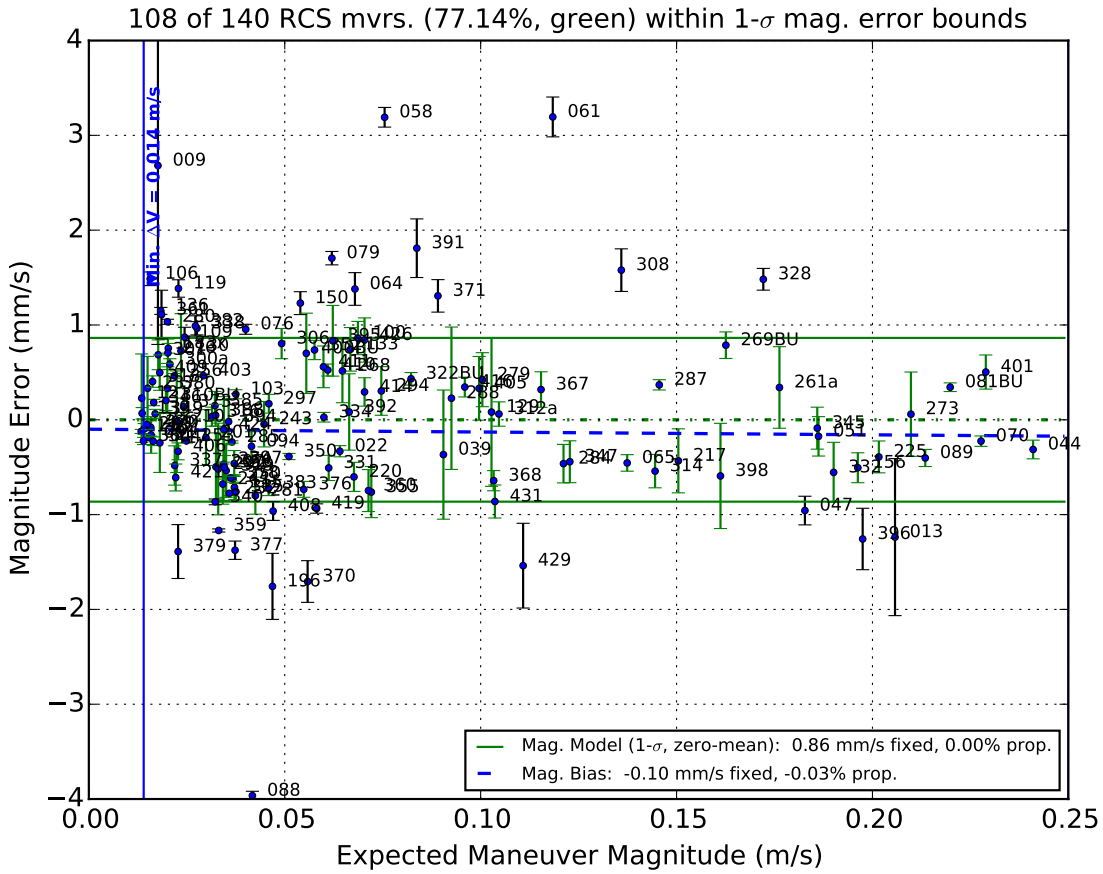
Magnitude Errors (Zero-Mean Model)



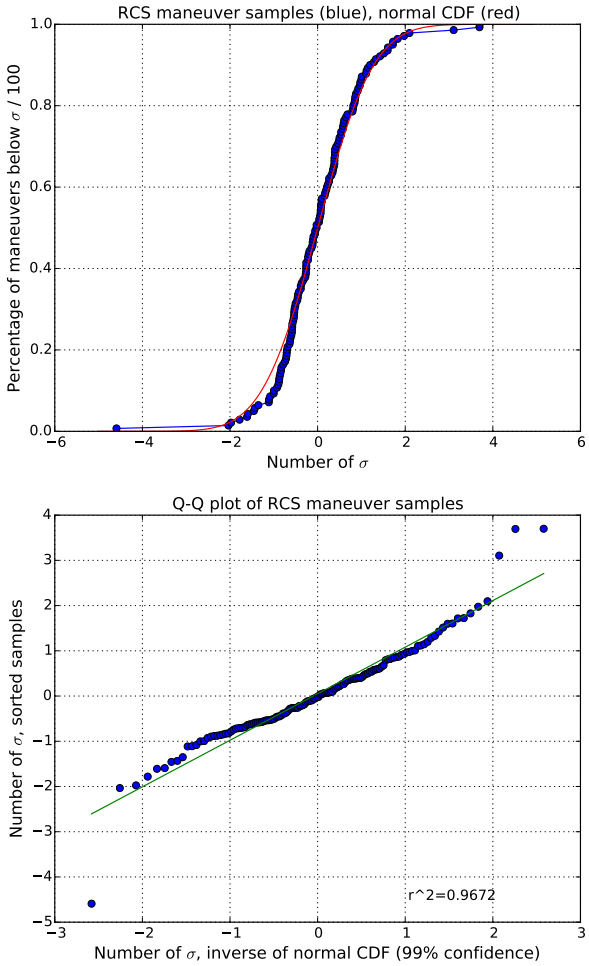
Mag-Error CDF & Q-Q Plots

2016-1B RCS Execution-Error Model (OTMs 183x–431 RCS Burns). *Model assumes no bias in data and is valid for B-branch RCS burns $\leq$ 0.3 m/s.*

RCS Magnitude Errors (2016-1AB Model)



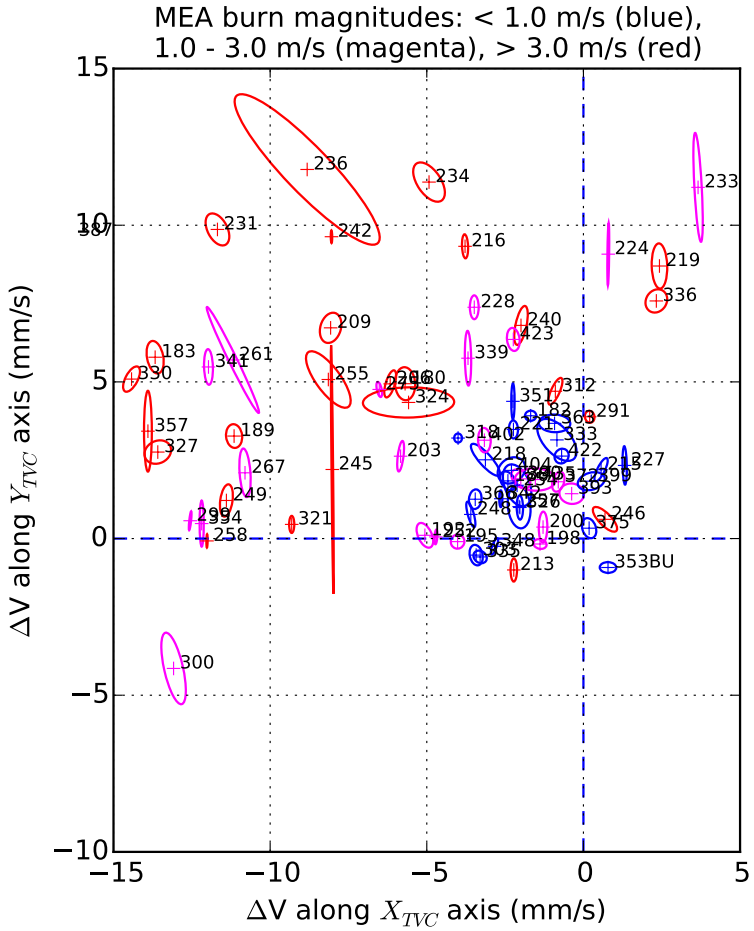
Magnitude Errors (Zero-Mean Model)



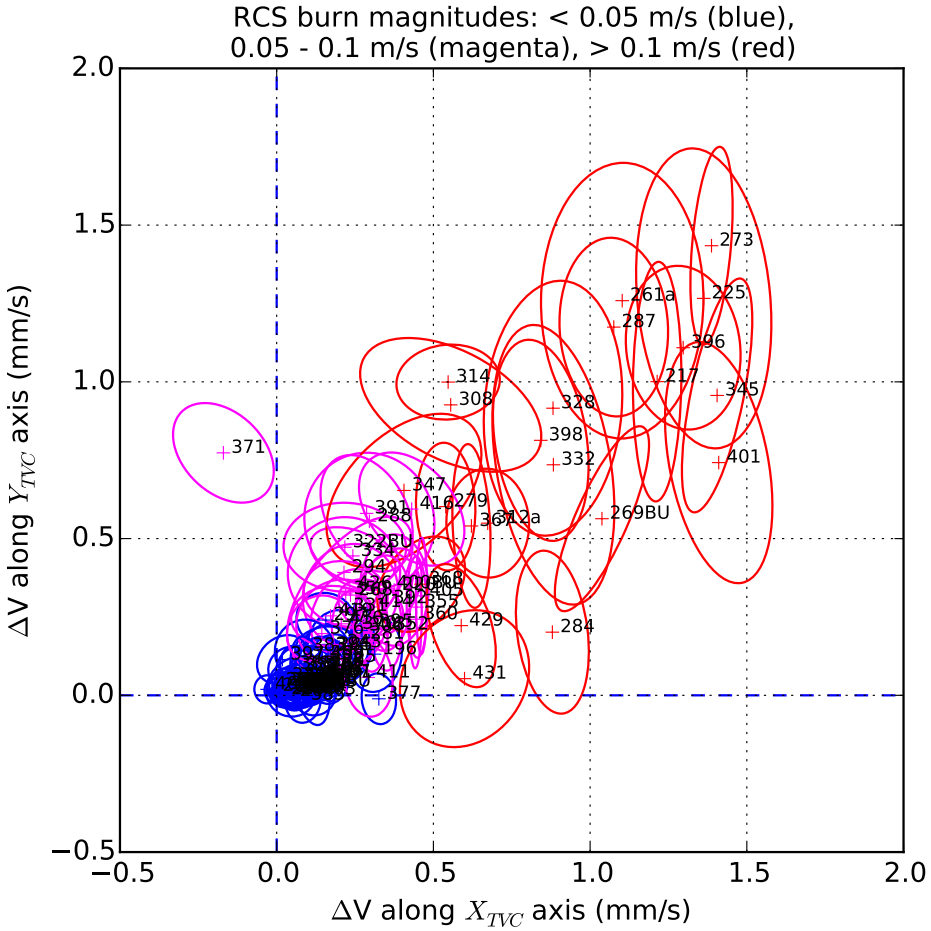
Mag-Error CDF & Q-Q Plots

2016-1AB RCS Execution-Error Model (OTMs 009–431 RCS Burns).
Model assumes no bias in data and is valid for all RCS burns $\leq$ 0.3 m/s.

Maneuver Pointing Errors in TVC Pointing Plane

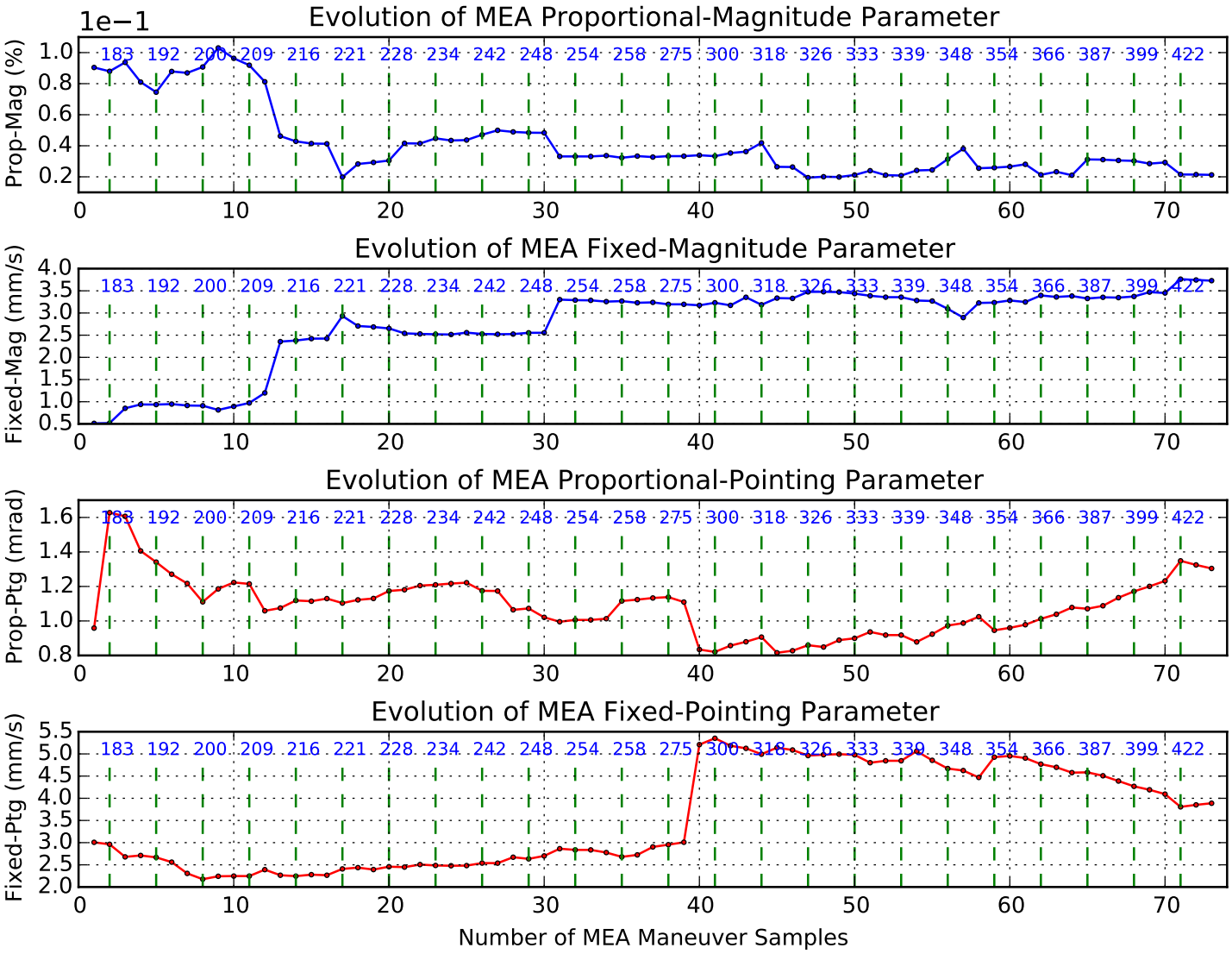


Main Engine (OTMs 180–435)

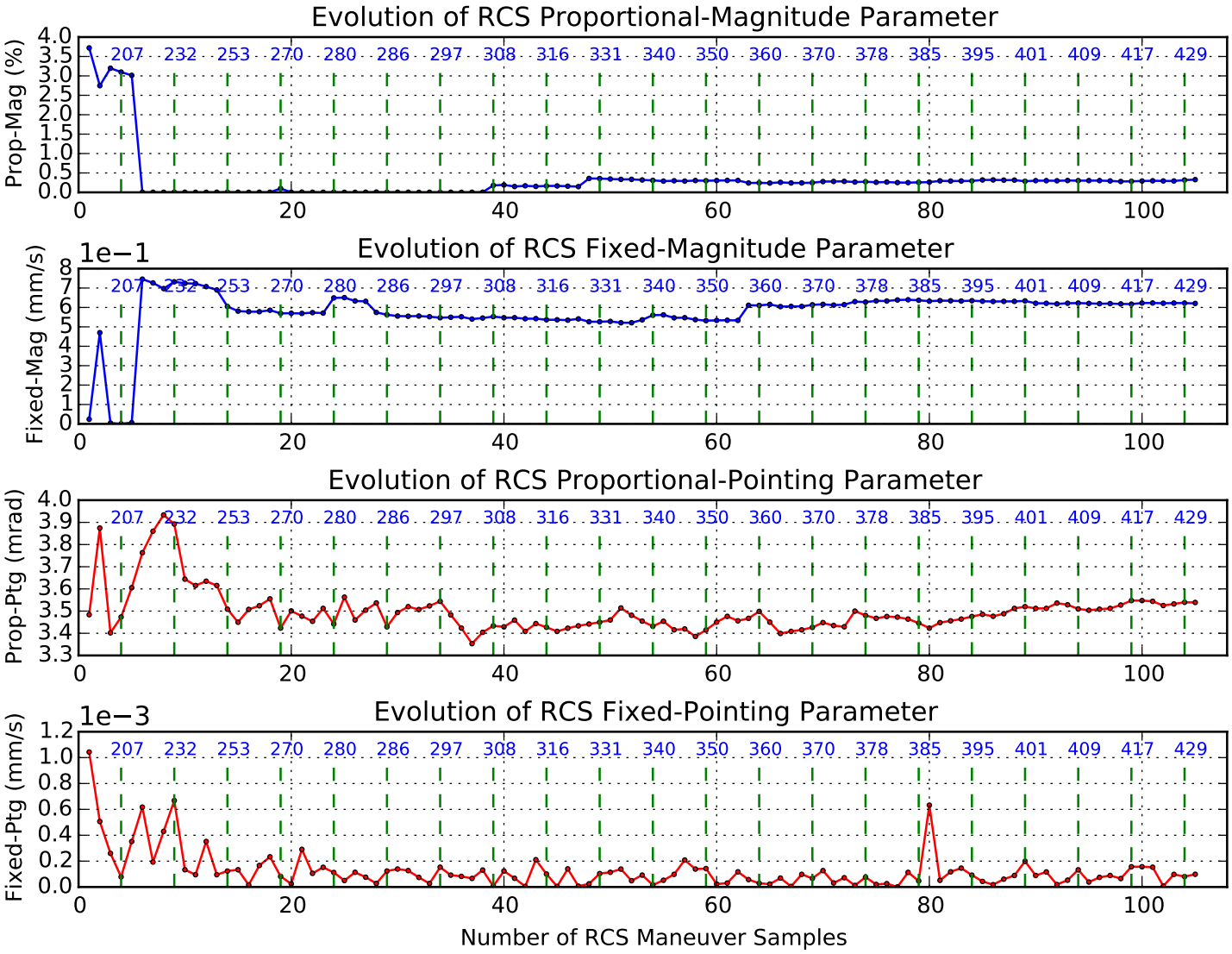


RCS B-Branch (OTMs 183x–431)

Evolution of 2016-1L Main Engine Gates-Model Parameters



Evolution of 2016-1B RCS Gates-Model Parameters



Summary of Execution-Error Models

Main Engine Execution-Error Models (1-σ)

		2008-01	2012-1	2016-1L	2016-2L	2016-1S
Magnitude	Proportional (%)	0	0.02	0.02	0.02	0
	Fixed (mm/s)	4.5	3.5	3.75	3.4	3.75
Pointing (per axis)	Proportional (mrad)	1.1	1.0	1.3	0.6	2.6
	Fixed (mm/s)	3.0	5.0	3.9	3.1	2.2
Main engine burns investigated		TCM-05–OTM-168	OTMs 180–326	OTMs 180–435	OTMs 180–435	OTMs 180–435
No. of main engine burns (excluded)		85 (9)	48 (0)	74 (0)	74 (0)	59 (15)
Valid for main engine burns		$\leq$25 m/s	$\leq$13 m/s	$\leq$13 m/s	$\leq$13 m/s	$\leq$5 m/s

RCS Execution-Error Models (1-σ)

		2008-01	2012-1	2016-1B	2016-2B	2016-1AB
Magnitude	Proportional (%)	0.4	0.4	0.3	0.45	0
	Fixed (mm/s)	1.0	0.5	0.6	0.6	0.85
Pointing (per axis)	Proportional (mrad)	9.0	4.5	4.15	1.65	4.3
	Fixed (mm/s)	0	0	0	0	0
RCS maneuvers investigated		TCM-19a–OTM-129	OTMs 183x–328	OTMs 183x–431	OTMs 183x–431	OTMs 009–431
No. of RCS maneuvers (excluded)		26 (11)	49 (2)	106 (2)	106 (2)	140 (12)
Valid for RCS maneuvers		$\leq$0.3 m/s A-branch	$\leq$0.3 m/s B-branch	$\leq$0.3 m/s B-branch	$\leq$0.3 m/s B-branch	$\leq$0.3 m/s All

Conclusion

- Efforts to preserve propellant have led to several execution-error model updates and calibrations of onboard flight parameters
  - By removing observed execution-error biases, propellant consumption may be reduced by increasing the number of maneuver cancellations and lessening the size of statistical maneuvers
  - Model updates have helped improve predictions of fuel usage and provided better *a priori* estimates for maneuver reconstructions
  - Updated models have supplied a better means to assess Cassini's maneuver performance
- Current 2012-1 main engine and RCS execution-error models in use since August 2012 were determined to be sufficient for the remainder of the Cassini Mission
  - Excellent performance of both propulsion systems since models were implemented (74 MEA burns and 106 RCS maneuvers)
  - Proposed hybrid RCS execution-error model found in this manuscript (2016-1AB RCS) may be utilized if both sets of RCS thrusters have degraded performance requiring a 'mixed-branch' solution

Backup Slides

Gates Execution-Error Model

- Gates-Model Parameters
  - Fixed and proportional-magnitude errors (σ_1 and σ_2)
  - Fixed and proportional-pointing errors (σ_3 and σ_4)
  - In a coordinate system whose x axis is $||$ to the desired $\Delta\mathrm{V}$, the Gates model covariance is:

$$P_{gates} = \begin{pmatrix} \sigma_1^2 + y^2\sigma_2^2 & 0 & 0 \\ 0 & \sigma_3^2 + y^2\sigma_4^2 & 0 \\ 0 & 0 & \sigma_3^2 + y^2\sigma_4^2 \end{pmatrix}$$

    where y is the magnitude of the maneuver $\Delta\mathrm{V}$
  - For any given maneuver, the Gates model is Gaussian $N(0, P_{gates})$
  - For a set of maneuvers with different $\Delta\mathrm{V}$ magnitudes, the Gates model is not Gaussian because the standard deviation is a function of y
  - Hence, standard deviations must be obtained by a method like maximum-likelihood estimation
- Construct likelihood expressions for the magnitude and pointing errors as functions of the Gates-model parameters
- Maximize likelihood functions to determine Gates-model parameters

Maximum-Likelihood Estimation

Magnitude error pdf:

$$f_m(x, v, \sigma_1, \sigma_2) = \left[2\pi(\sigma_1^2 + v^2\sigma_2^2)\right]^{-1/2} \exp\left[-\frac{1}{2}\frac{(x-\mu_m)^2}{\sigma_1^2 + v^2\sigma_2^2}\right]$$

where x is the magnitude error, $\mu_m = \mu_1 + v\mu_2$ is the mean magnitude error, μ_1 is the fixed-magnitude error bias, and μ_2 is the proportional-magnitude error bias. Likelihood function for magnitude errors:

$$L_m(\sigma_1, \sigma_2) = \prod_{i=1}^{N} f_m(x_i, v_i, \sigma_1, \sigma_2)$$

Pointing error pdf (two-dimensional vector):

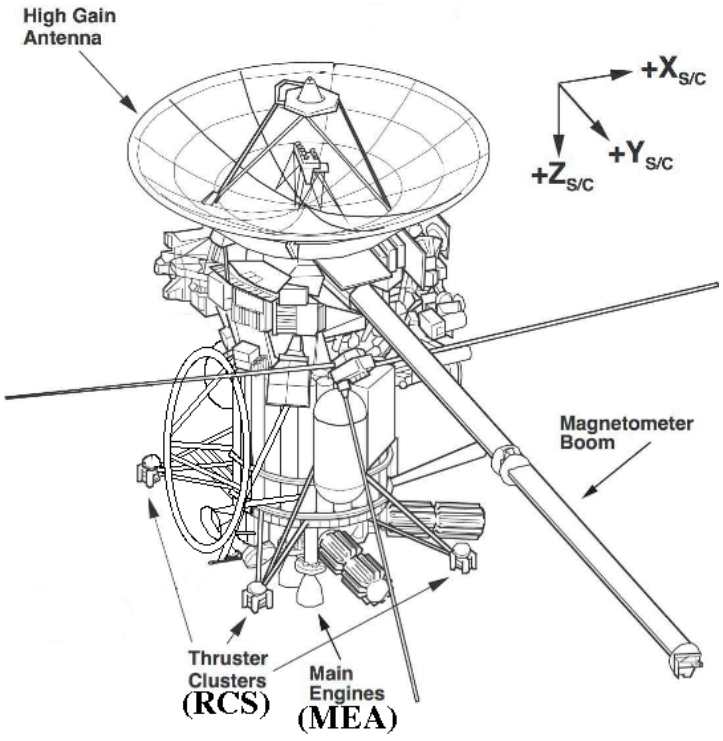
$$f_p(\vec{x}, v, \sigma_3, \sigma_4) = \left[\sqrt{2}\pi(\sigma_3^2 + v^2\sigma_4^2)\right]^{-1} \exp\left[-\frac{1}{2}\frac{|\vec{x} - \vec{\mu_p}|^2}{\sigma_3^2 + v^2\sigma_4^2}\right]$$

where $\vec{x}$ is the pointing error vector in units of velocity, $\vec{\mu_p} = \vec{\mu_3} + v\vec{\mu_4}$ is the mean pointing error, $\vec{\mu_3}$ is the fixed-pointing error bias, and $\vec{\mu_4}$ is the proportional-pointing error bias. Likelihood function for pointing errors:

$$L_p(\sigma_3, \sigma_4) = \prod_{i=1}^{N} f_p(\vec{x_i}, v_i, \sigma_3, \sigma_4)$$

Processing of Maneuver Data

- Maneuver errors not computed by simply differencing design ΔV from reconstructed ΔV
- Expected ΔV = design ΔV + ΔV events
- Thrust-vector-control (TVC) coordinate frame
  - Z_{TVC} || to expected ΔV
  - X_{TVC} || to projection of $X_{S/C}$ onto plane $\perp$ to Z_{TVC}
  - Y_{TVC} completing the right-handed system.



- Execution errors expressed with two $\perp$ components:
  - Magnitude errors: differencing the lengths of the reconstructed and expected ΔV vectors
  - Pointing errors: vector differences of the reconstructed and expected ΔVs projected onto the pointing plane ($\perp$ to Z_{TVC}).