Orbit Determination Accuracy Analysis of the Magnetospheric Multiscale Mission During Perigee Raise

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Daniel A. Pachura, Matthew A. Vavrina

a.i. Solutions/NASA Flight Dynamics Facility

J. Russell Carpenter, Cinnamon A. Wright

NASA Goddard Space Flight Center
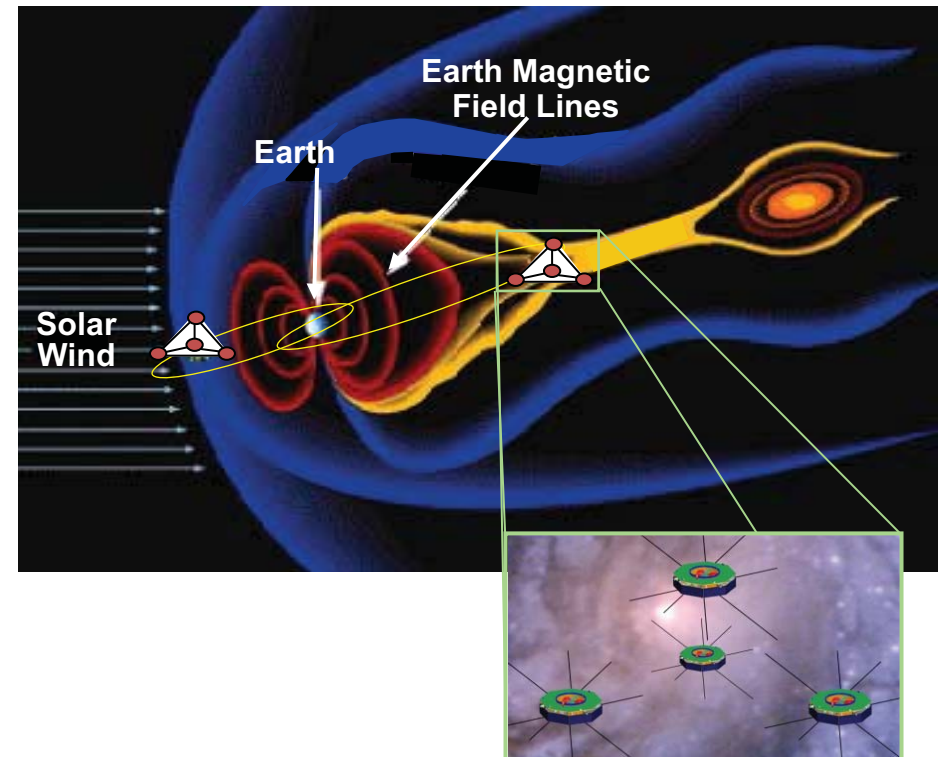
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FLIGHT DYNAMICS FACILITY
NAVIGATION & MISSION DESIGN BRANCH
NASA GSFC

MMS Mission Overview

- Formation of 4 identical spacecraft in a highly elliptical Earth orbit
- Studying fundamental plasma processes in Earth's magnetosphere
- Launching in 2015
- 2 year operational life

Orbit Overview

- **Launch orbit**
  - 240 km x 12 Earth Radii (R_E)
  - Inclined at 28.5
  - ~24 hour period
- **Phase 1 orbit**
  - 1.2 R_E x 12 R_E
- **Phase 2 orbit**
  - 1.2 R_E x 25 R_E
- **Executes 5 perigee raise maneuvers near apogee within 2 weeks of launch**
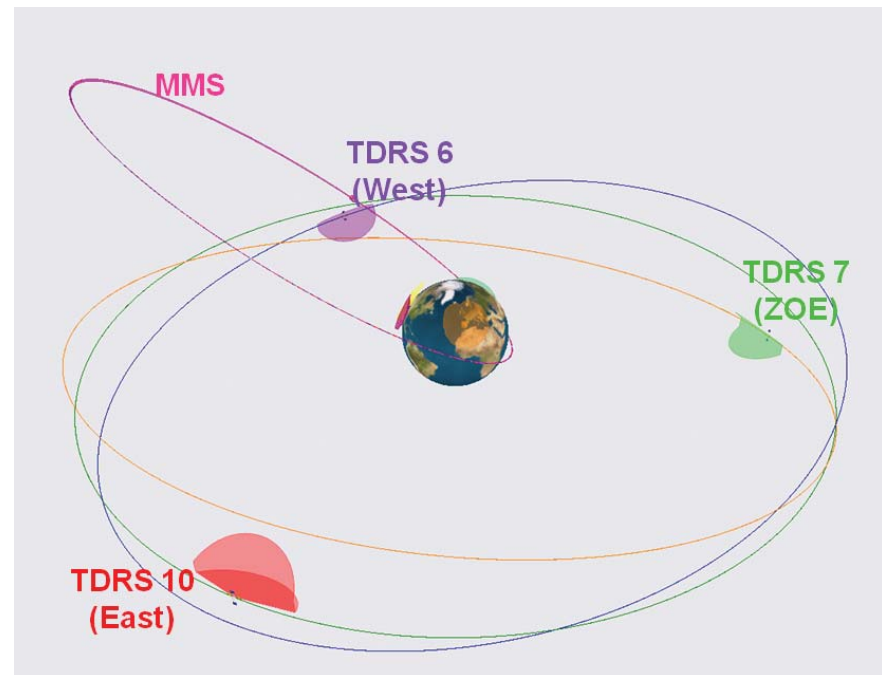
Orbit Determination Overview

- Spacecraft Separation to Launch + 8 weeks
  - TDRS range and Doppler and DSN Doppler used for orbit determination (OD)
  - Performed by the Flight Dynamics Facility (FDF)
    - Early orbit solutions from a batch least squares method implemented in Goddard Trajectory Determination System (GTDS)
    - Nominal support from extended Kalman filter implemented in Orbit Determination Toolkit (ODTK)
- Launch + 8 weeks to mission end-of-life
  - GPS data used for OD
  - Performed onboard spacecraft
    - NASA developed GPS-enhanced Onboard Navigation System (GEONS)

Maneuver Support Operations Concept
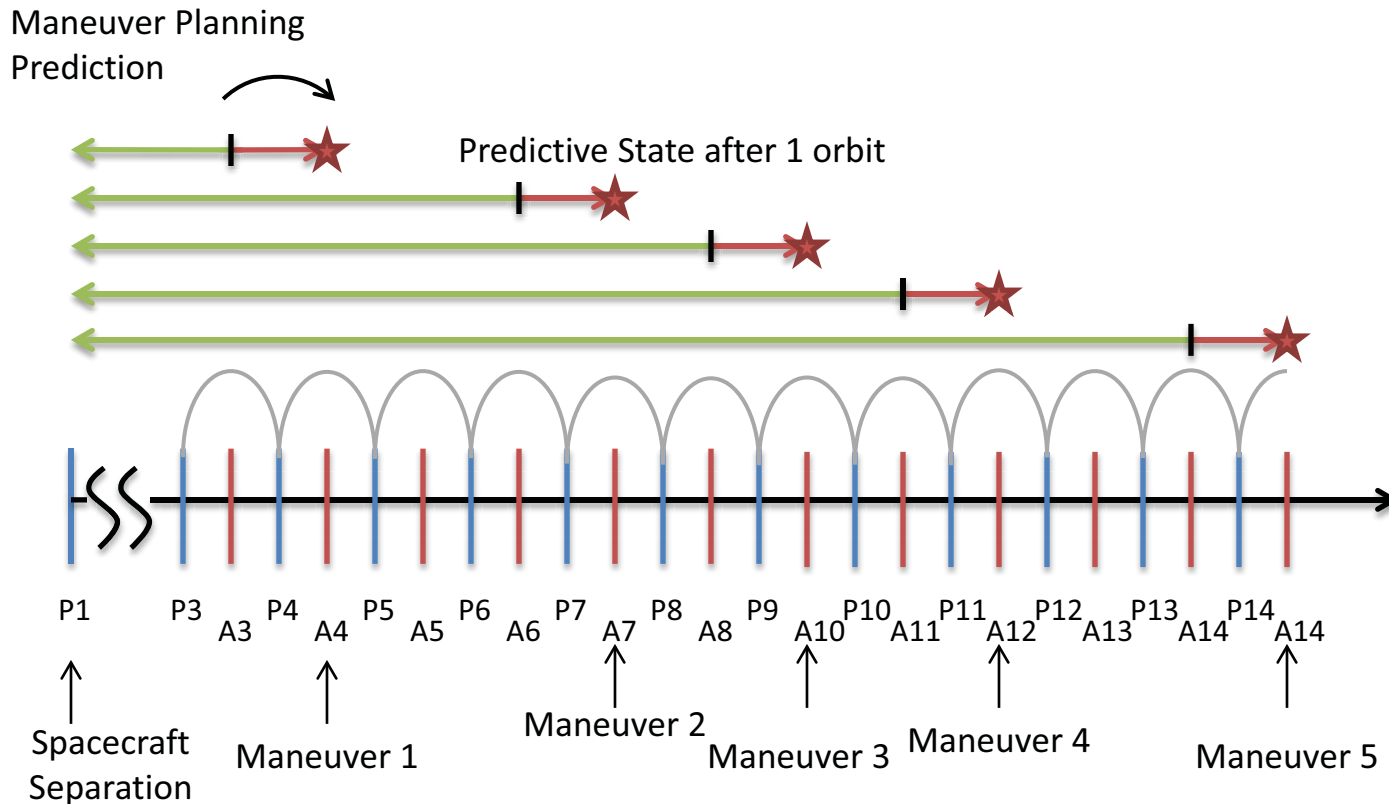
Perigee raise support requires accurate predictions at a nearly every-other-orbit cadence

Thruster Calibration Support

Definitive State

Tracking

P1   P3   A3   P4   A4   P5   A5

Spacecraft
Separation
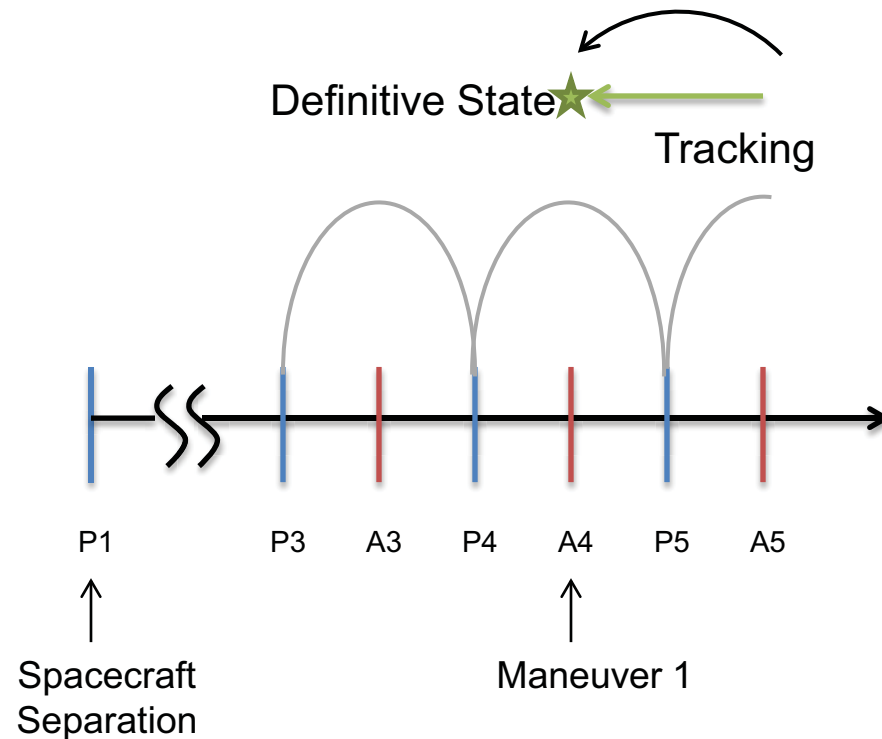
Maneuver 1

An accurate post-maneuver state is needed within 1 orbit to calibrate thruster performance and plan for the upcoming maneuvers

Accuracy Requirements

Definitive Velocity Error

- Solution required 1 revolution after 1st maneuver
- Magnitude of the velocity error must be
  - Less than 5 mm/s, or
  - Less than 1% of preceding maneuver's magnitude, whichever is greater
- 1% threshold ranges from about 30 - 180 mm/s

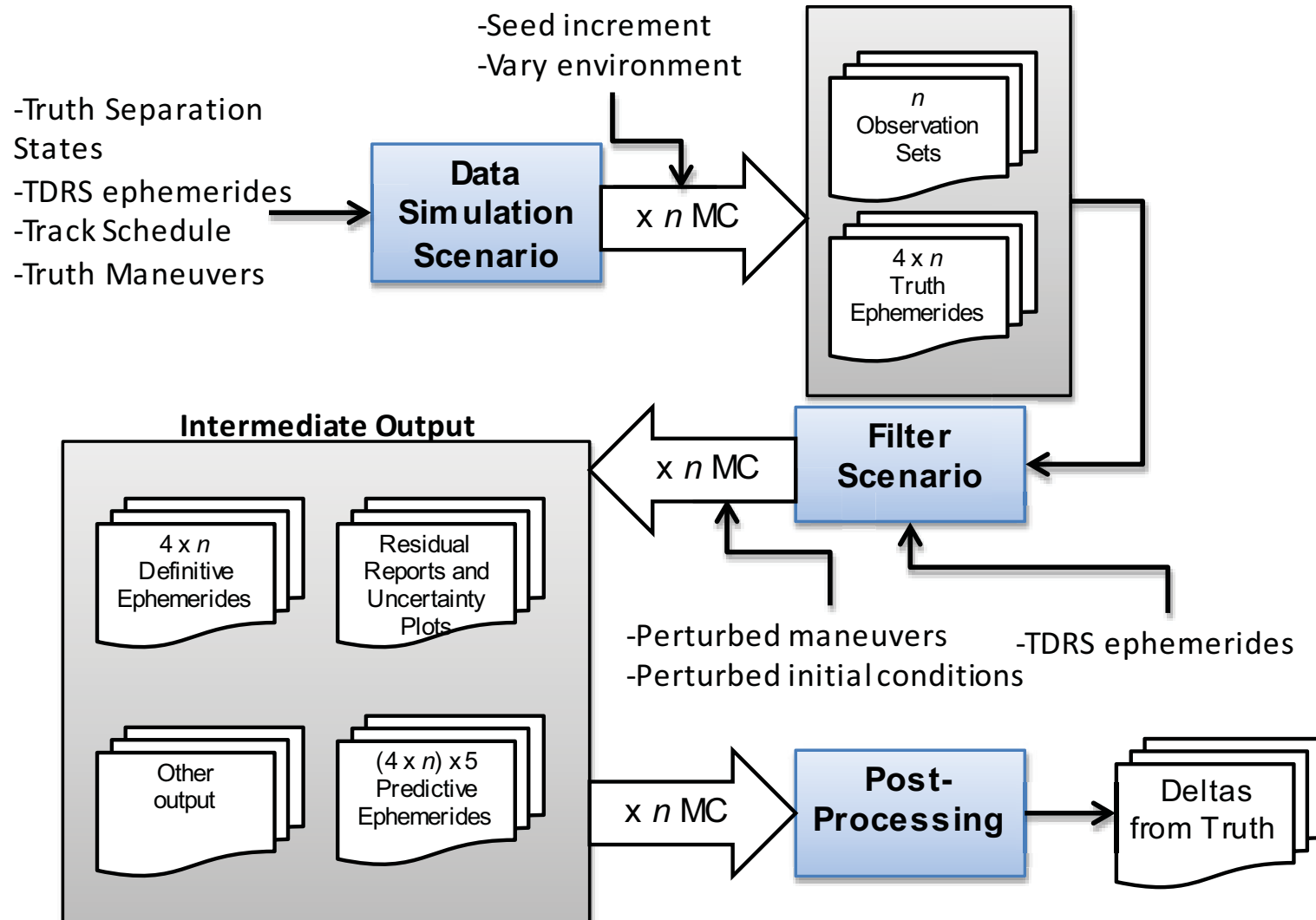## Predictive Velocity Error

- Prediction required 1 revolution prior to each maneuver
- Magnitude of the velocity error must be
  - Less than 5 mm/s, or
  - Less than 1% of upcoming maneuver's magnitude, whichever is greater
- 1 % threshold ranges from about 30 – 300 mm/s
- 5 mm/s is evaluation threshold

Requirements Validation With Monte Carlo Approach

- Monte Carlo analysis to validate requirements
  - Variation of a range of orbit parameters simultaneously
  - Characterize filter performance and response to measurement and modeling errors
- Simulate tracking observations and filter in ODTK
  - Exercises the operational toolset

Analysis Architecture

- Truth Separation States
- TDRS ephemerides
- Track Schedule
- Truth Maneuvers

- Seed increment
- Vary environment

Data Simulation Scenario

x *n* MC

n Observation Sets

4 x *n* Truth Ephemerides

Filter Scenario

x *n* MC

- Perturbed maneuvers
- Perturbed initial conditions

- TDRS ephemerides

Intermediate Output

4 x *n* Definitive Ephemerides

Residual Reports and Uncertainty Plots

Other output

(4 x *n*) x 5 Predictive Ephemerides

x *n* MC

Post-Processing

Deltas from Truth

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Analysis Setup

Simulator

- Reference initial states
- Reference maneuver time, magnitude, and direction
- Within each Monte Carlo Sample varied
  - Atmospheric Density
  - Ballistic Coefficient
  - Solar Radiation Pressure
  - Range observation noise and bias
 - Doppler observation noise

Filter

- Seeded with perturbed initial state
  - 100 m 1-σ position random error
  - 10 cm/s 1-σ velocity random error
- "Mis-modeled" maneuver magnitude and direction
  - Random errors of 2%/√3 maneuver magnitude along velocity vector and in the plane normal to velocity vector

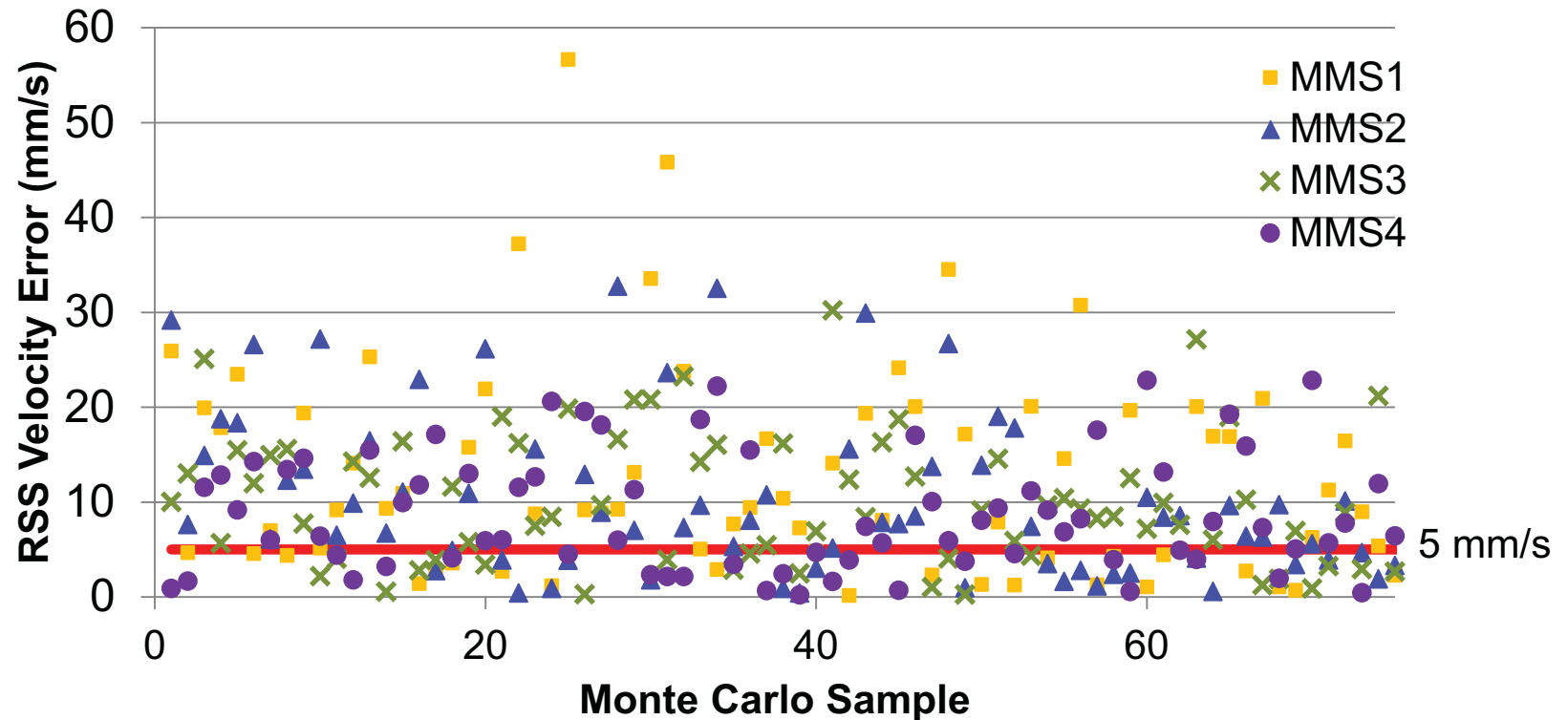# Definitive Velocity Error Results
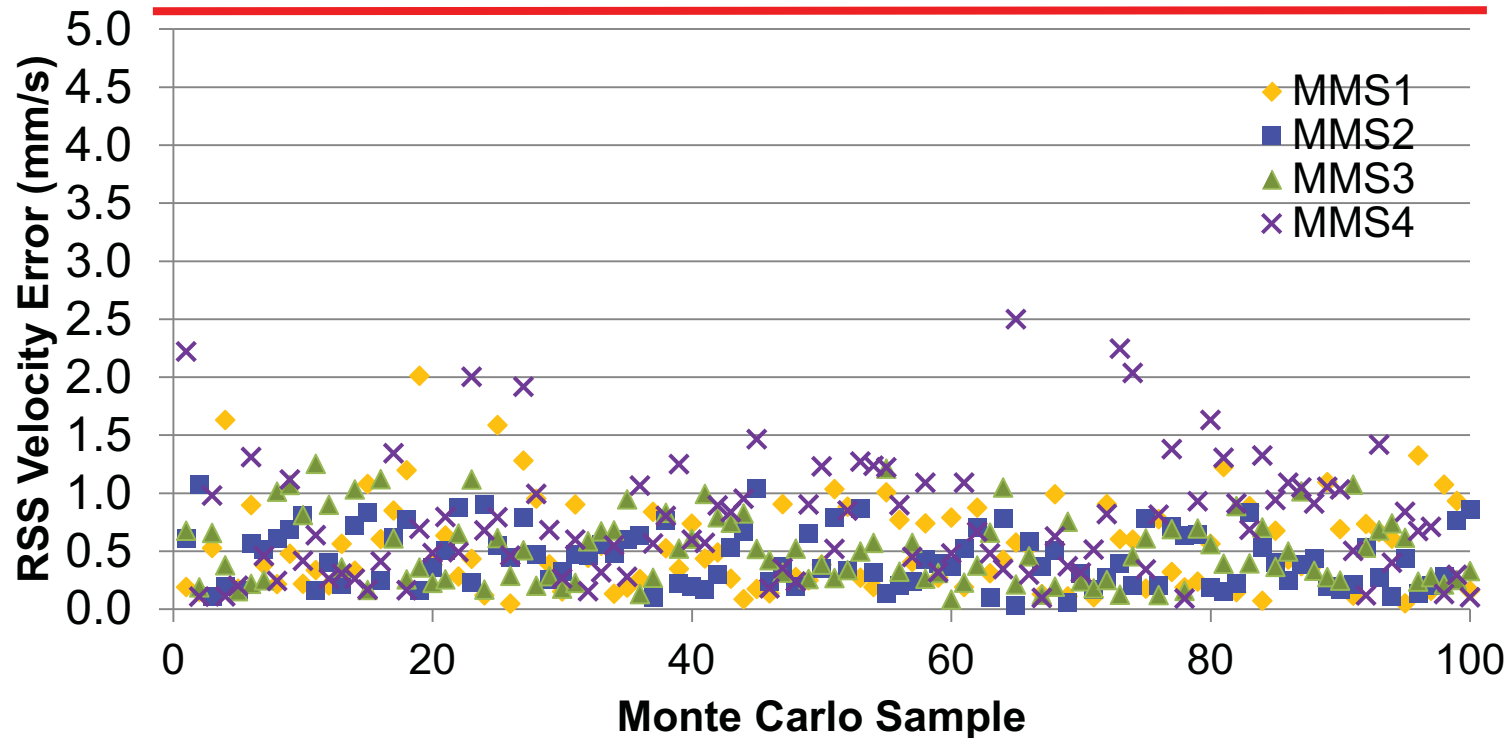
Definitive velocity error one orbit after first maneuver well under 5 mm/s velocity error threshold
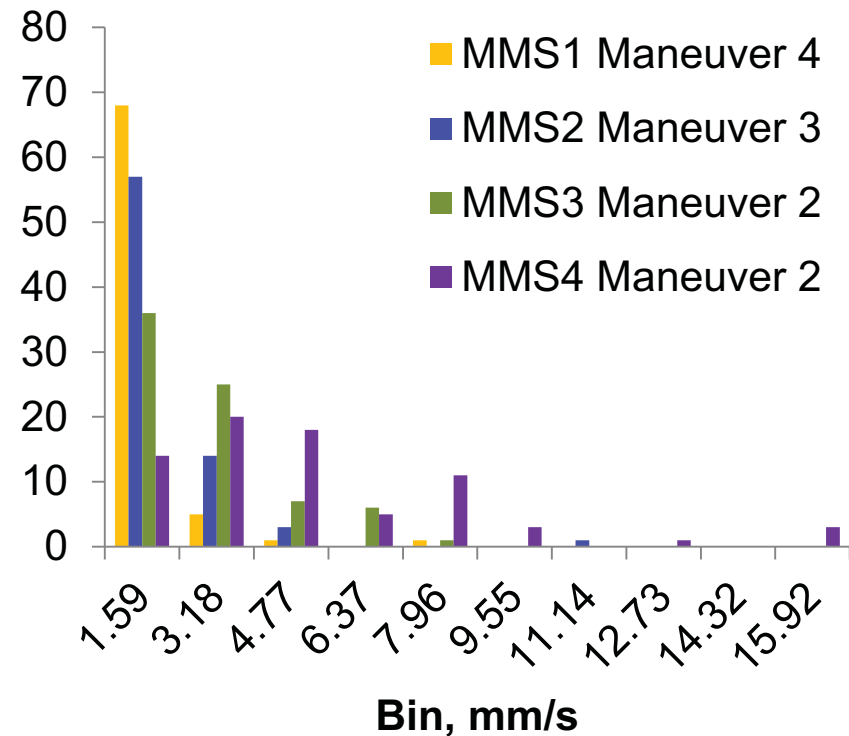
Worst Case Definitive Error
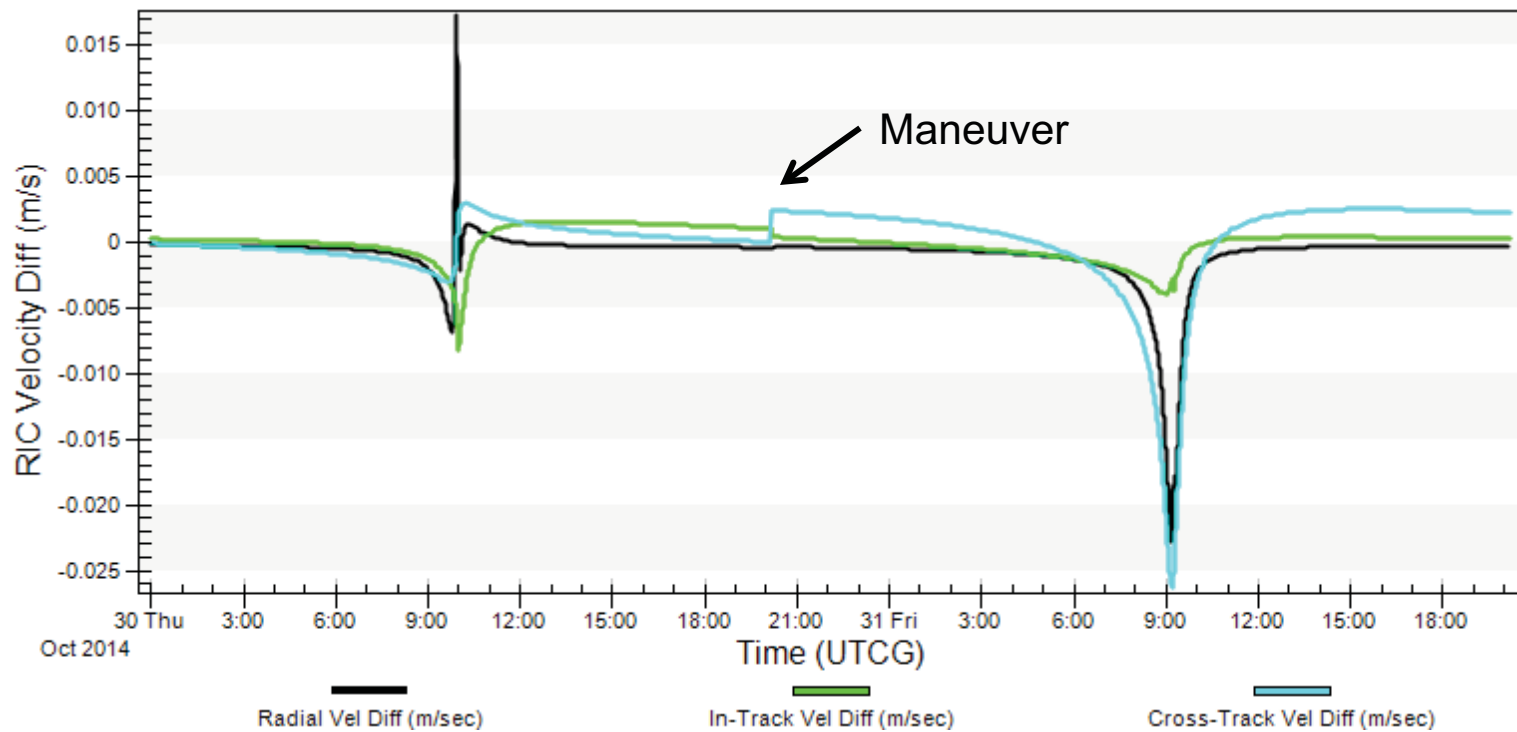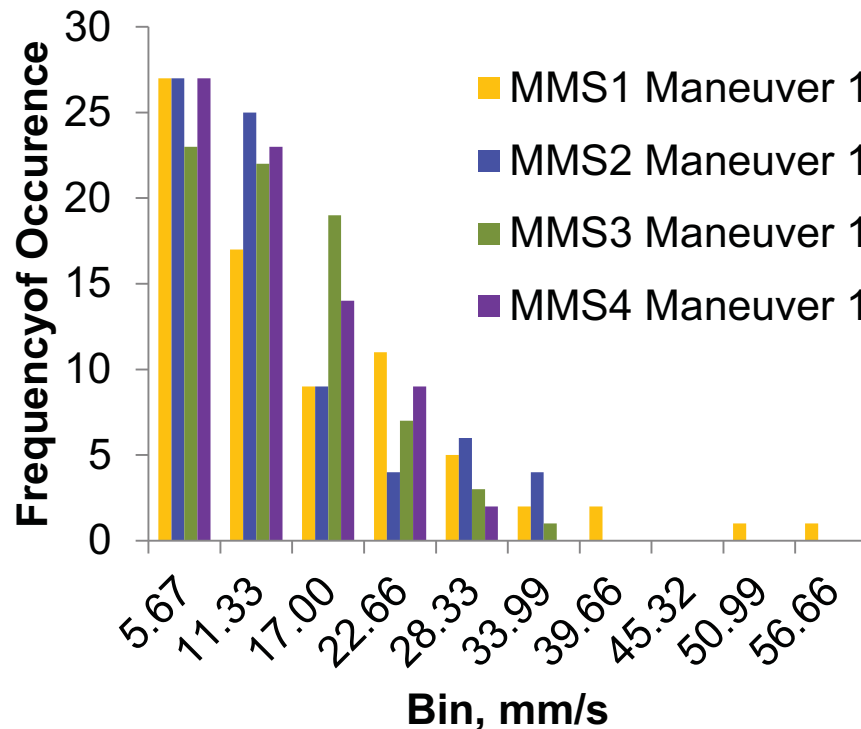

Definitive error low through most of the orbit

Predictive Velocity Error Results

Predictive velocity error one orbit prior to 1st maneuver well over 5 mm/s velocity error threshold, but under 1% of maneuver magnitude

Predictive Error Histograms Of Poor Predictions

First maneuver and MMS3 and MMS4's second maneuver have consistent and significant errors greater than 5 mm/s

Predictive Error Growth

Sub-5mm/s Monte Carlo Sample

Worst Case Monte Carlo Sample
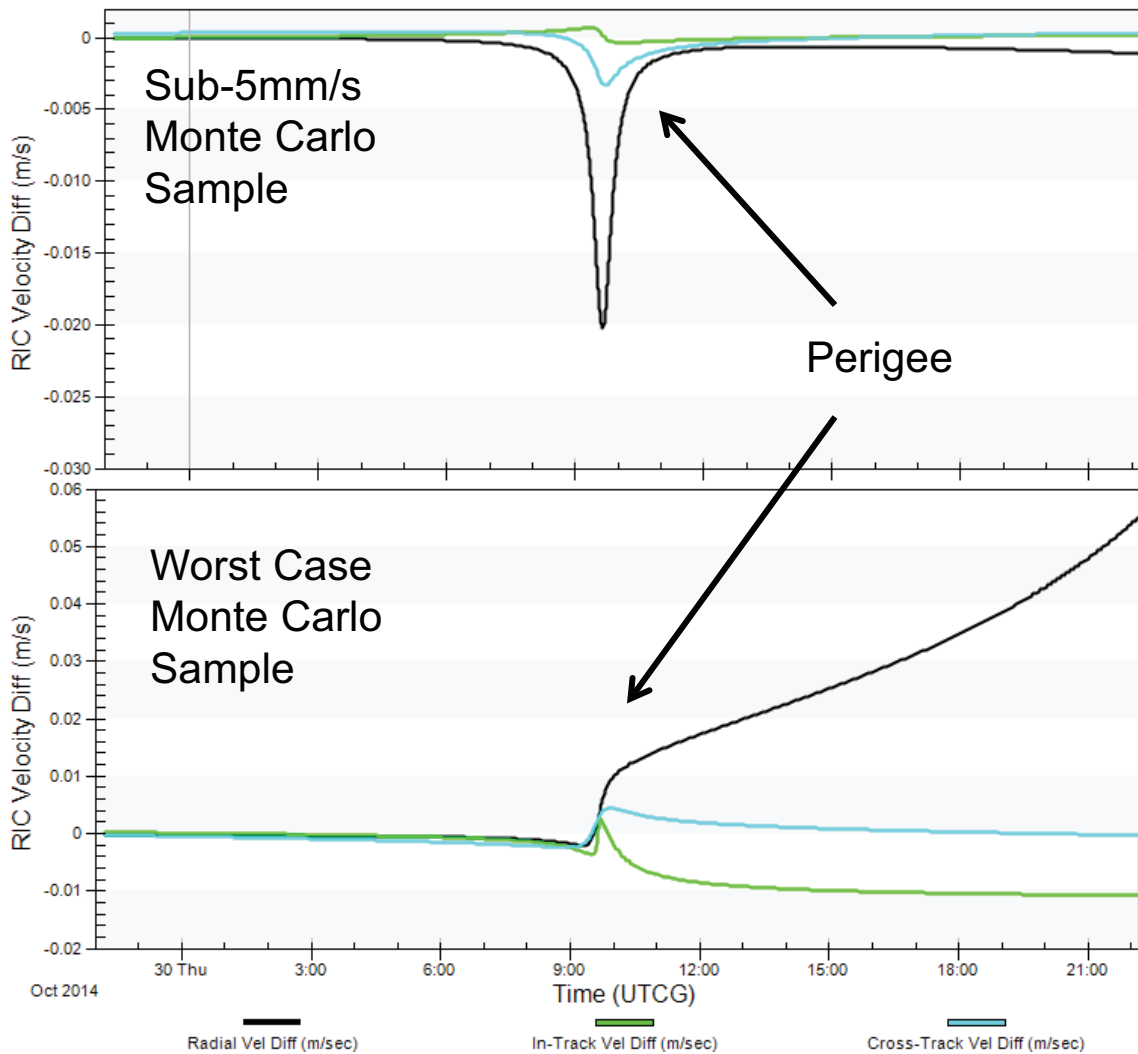
Perigee

Cases failing to meet 5 mm/s threshold begin diverging following perigee

Atmospheric Density Variation During Transit
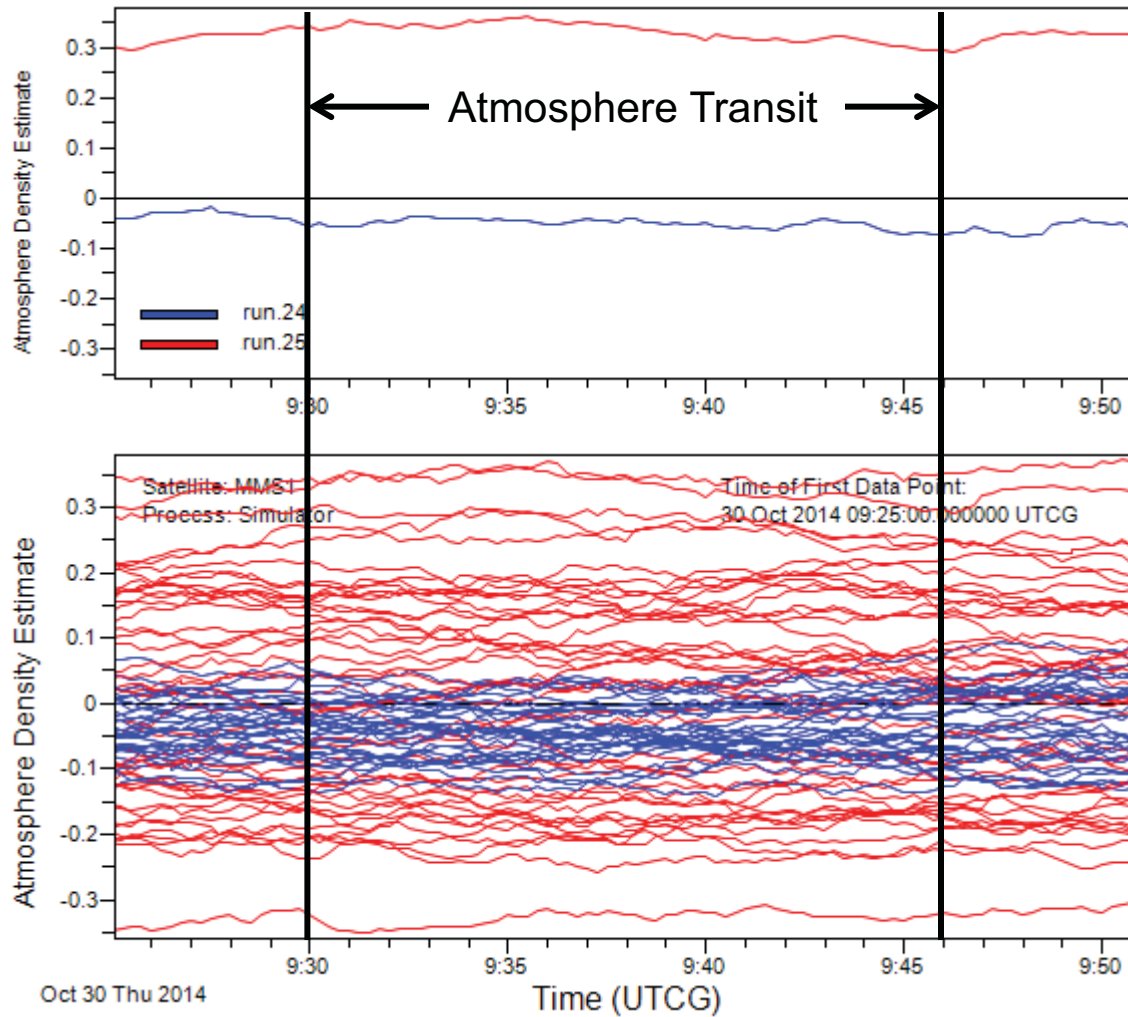
Red error > 5 mm/s
Blue error < 5 mm/s

Monte Carlo samples with error less than 5 mm/s error had minimal variation off of the nominal density

Atmosphere Model

- Jacchia-Roberts implemented in ODTK
- Solar Flux
  - F10/F10bar = 100
  - Ap = 10
  - From Schatten predicts for late 2014
- σ of density is driven by ODTK internal model
  - Implemented as a function of perigee altitude
  - Ranges from ~0.1-0.2 for 200-400 km perigee altitude

Prediction Challenges

Perigee Altitudes After Each Maneuver				
	MMS1	MMS2	MMS3	MMS4
Separation, km	240	244	242	241
Post-Maneuver 1, km	520	410	355	310
Post-Maneuver 2, km	830	440	680	610
Post-Maneuver 3, km	1230	1170	1120	1120
Post-Maneuver 4, km	1430	1400	1340	1230
Post-Maneuver 5, km	1480	1460	1390	1280

- High velocity transit, 10.5 km/s, through low perigee altitude
- Higher density of atmosphere
- Significant orbit perturbations
- Atmospheric model variation near perigee critical

Conclusion

- High velocity transit combined with atmospheric density variations drive predictive errors

- Able to meet 5 mm/s definitive velocity error threshold

- Able to meet 1% maneuver magnitude predictive velocity error, but not 5 mm/s error threshold

- Monte Carlo approach provides valuable insight for mission design and requirements validation
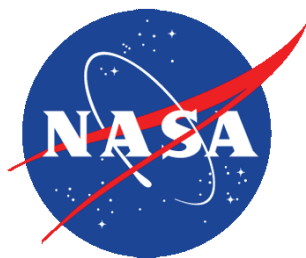
BACKUP

Definitive Error Statistics

	MMS1	MMS2	MMS3	MMS4
Mean Velocity Error, mm/s	0.5	0.4	0.5	0.8
Mean Velocity Error, mm/s	0.4	0.4	0.4	0.7
Maximum Error, mm/s	2.0	1.1	1.3	2.5
1 % Maneuver Magnitude, mm/s	172.9	98.7	63.8	34.4

Predictive Error Statistics

		MMS1	MMS2	MMS3	MMS4
Maneuver 1	Median Velocity Error, mm/s	9.18	7.83	9.09	7.29
	Mean Velocity Error, mm/s	12.61	10.23	10.20	8.74
	Maximum Velocity Error, mm/s	56.65	32.75	30.21	22.83
	1 % Maneuver Magnitude, mm/s	173.00	98.70	63.80	34.40
Maneuver 2	Median Velocity Error, mm/s	0.41	1.06	1.72	3.67
	Mean Velocity Error, mm/s	0.47	1.24	2.01	4.30
	Maximum Velocity Error, mm/s	1.39	3.65	6.63	15.91
	1 % Maneuver Magnitude, mm/s	204.30	212.40	214.80	207.00
Maneuver 3	Median Velocity Error, mm/s	0.53	0.67	0.91	0.44
	Mean Velocity Error, mm/s	0.63	1.17	1.23	0.49
	Maximum Velocity Error, mm/s	3.40	10.69	4.81	1.37
	1 % Maneuver Magnitude, mm/s	261.10	273.10	273.20	267.60
Maneuver 4	Median Velocity Error, mm/s	0.41	0.25	0.39	0.25
	Mean Velocity Error, mm/s	0.69	0.31	0.51	0.26
	Maximum Velocity Error, mm/s	6.99	0.89	3.07	0.71
	1 % Maneuver Magnitude, mm/s	127.40	134.70	133.30	133.80
Maneuver 5	Median Velocity Error, mm/s	0.16	0.17	0.19	0.19
	Mean Velocity Error, mm/s	0.20	0.17	0.20	0.22
	Maximum Velocity Error, mm/s	1.06	0.40	0.48	0.57
	1 % Maneuver Magnitude, mm/s	19.30	19.70	18.50	18.50