Initial Satellite Formation Flight
Results from the Magnetospheric MultiScale Mission

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Introduction

- MMS Formation Flying Dynamics
- MMS Onboard Navigation System
- Formation Maneuver Design Process
- Formation Maneuver Execution Process
- Formation Maneuver Results
MMS Spacecraft

- Width: 3.15 m
- Height: 1.23 m
- Weight: ~ 1,290 kg
- SDP-Wire Booms (x4): 60 m
- ADP-Antenna Mast (x2): 14.75 m
- Magnetometer Booms (x2): 5 m

1. SDP-Wire Booms
2. ADP-Antenna Masts
3. Magnetometer Booms
Formation at Apogee
Formation at Perigee
MMS Onboard Nav System: GEONS

- GEONS processes GPS L1 signals in an Extended Kalman Filter (EKF) and uses a high-fidelity dynamics model to estimate the spacecraft’s position, velocity, clock bias with respect to GPS time, clock bias rate, and clock bias acceleration.

- GEONS predictive performance and maneuver planning capability were evaluated by comparing definitive data with the predictive solutions generated in FreeFlyer 6.9.1.
GEONS vs Predicted Solutions Differences

NavQA Ephemeris Difference M1A
REF: Deploy.GGSS/NavQA.ITPSYPP.Ephom

Graphs showing differences between GEONS and predicted solutions over time, with various plots illustrating deviations in position and other parameters.
Number of GPS Space Vehicles Tracked

Time Series

Period-folded Ensemble
with mean and ~99% confidence intervals
Formation Maneuver Design

- Target formation has shape of a regular tetrahedron in the region-of-interest (ROI) (TA ~160-200 deg)
- Instantaneous quality factor $Q(t) \in [0,1]$ which is a product of two terms
  - $Q_s(t)$ associated with scale size (allows for ‘breathing’)
  - $Q_v(t)$ measures how close the shape is to a regular tetrahedron
- Science requirement $T_Q$, the time the formation spends in the ROI with a $Q(t)$ above 0.7
  - $T_Q \in [0,100]$; Current science requirement is to have $T_Q > 80$, on average, for each mission phase

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T_Q = \frac{100}{N_{ROI}} \sum_{i=1}^{N_{ROI}} M_i \quad \text{where} \quad \begin{cases} 
M_i = 1 & \text{if} \quad Q(t_i) \geq 0.7 \\
M_i = 0 & \text{if} \quad Q(t_i) < 0.7
\end{cases}
\]

\[
Q(t_i) = Q_s(t_i) Q_v(t_i)
\]
Formation Man. Execution Process (1/2)

• Perform preliminary design of maneuvers
• Decide the staggering sequence and reference spacecraft
• Check the results based on daily OD data and the FDA reruns
• Finalize the staggering sequence; submit this to scheduling/operations
• Deliver preliminary DV tables to GEONS team
• Perform preliminary and then final detailed simulation (using the tool CHiFi) to verify expected fuel use and check that the maneuvers do not violate any spacecraft safety constraints (boom bending moments, etc.)
• Evaluate the effects of the maneuvers on SMA values, orbit planes, QF evolution
• Perform Monte Carlo runs to determine safety in the face of maneuver execution errors, as well as QF lifetime
Formation Man. Execution Process (2/2)

• Present results at Command Authorization Meeting (CAM) that is held between the FOT and FDOA teams

• Monitor FM1 burns; reconstruct fuel use and SMA changes from spacecraft data downlinked at end of maneuver pass

• Use the navigation data downlinked at the post-perigee passes to evaluate maneuver errors and determine if tweaking of FM2 is necessary: if so, perform Delta-CAM and upload new maneuver commands

• Monitor FM2 burns; reconstruct fuel use and SMA changes from maneuver pass data

• Use nav data downlinked at the post-perigee passes to evaluate the final formation orbits ➔ initial data for the generation of the next set of maneuvers occurring in 2 or more weeks
Formation Side Length
Average of Mean values over ROI

Date of ROI Apogee

Side Length (km)

No Formation
160km
60km
40km
25km
10km

Mean Instantaneous Sidelength in RoI (160 km)
Formation Quality Evolution Over Mission
Quality Factor Evolution, Two 40 km
Six Inter-Spacecraft Ranges Over Rev
SMA over Set of FM Maneuvers
Remaining Fuel Each Spacecraft
Delta-V Execution Error (Magnitude)
Delta-V Execution Error (Magnitude)
Delta-V Execution Error (Direction)
Conclusions

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