Solar Sail Torque Model Characterization for the Near Earth Asteroid Scout Mission

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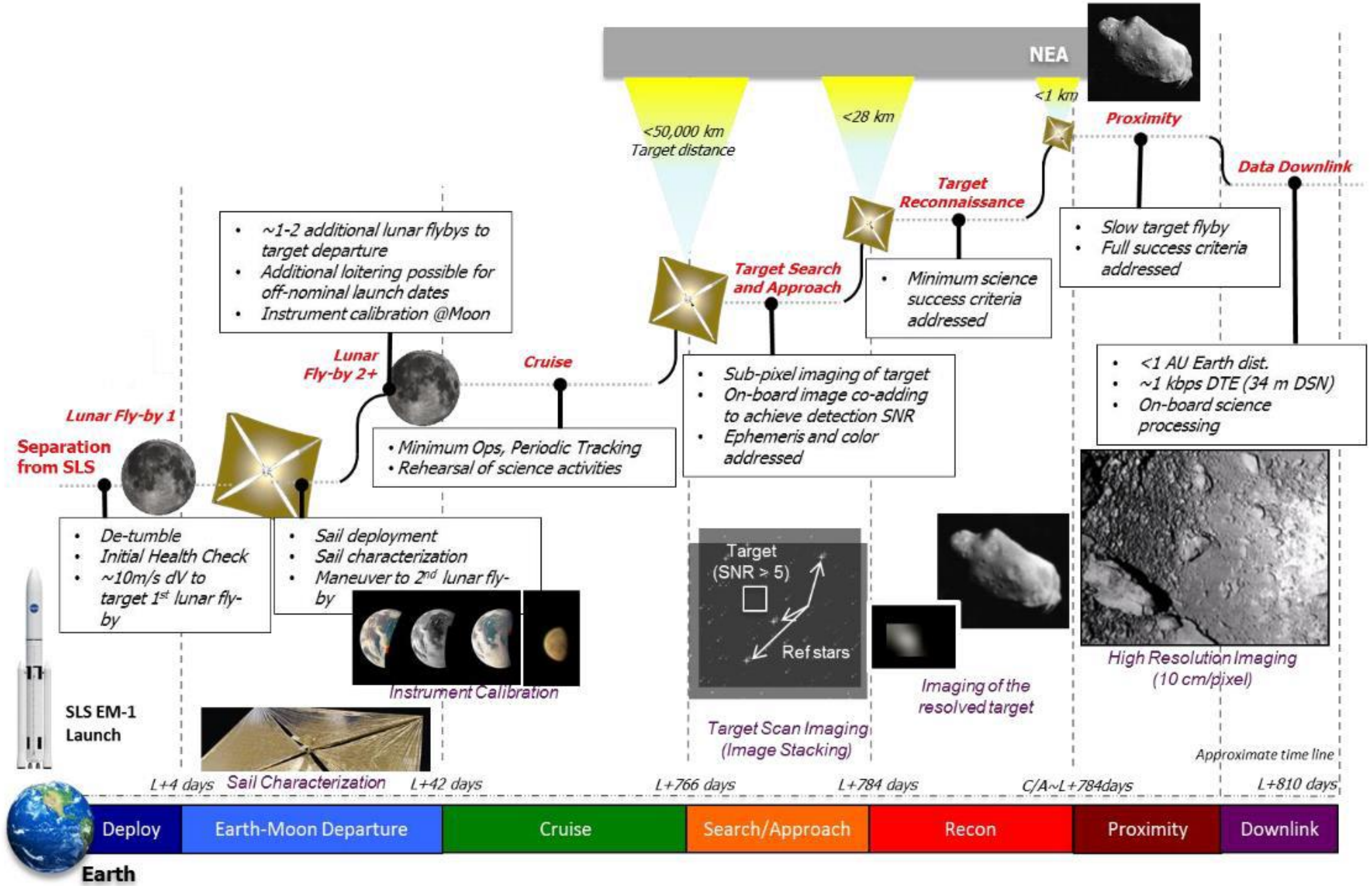
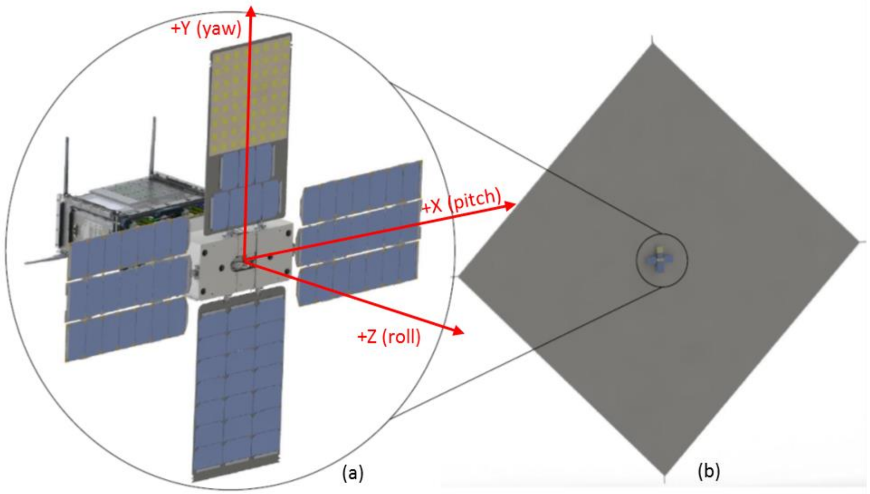
Introduction

- Accurate navigation of a solar sail requires
  - Accurate thrust vector control
  - Accurate sail attitude control
- Sail attitude control
  - Sizing and design depend on knowledge of solar torque
  - Torques driven by 3D shape of sail
  - Uncertainties in sail shape result in uncertain torques
- Sail torque characterization
  - Using flight telemetry, mission data, and models
  - Update torque model parameters
  - Understand attitude control dynamics of mission being flown
  - Improve control system design for follow-on sails of similar design

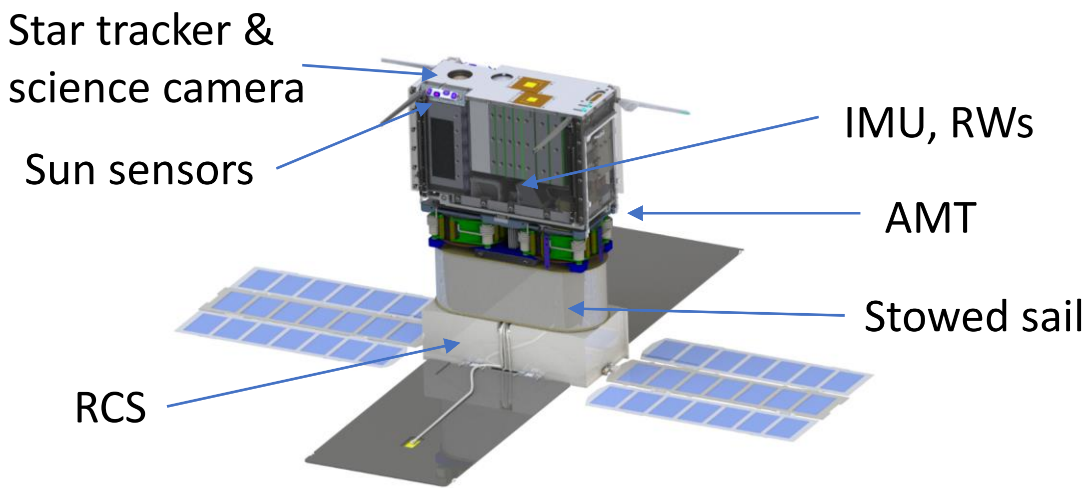
Near Earth Asteroid (NEA) Scout Mission

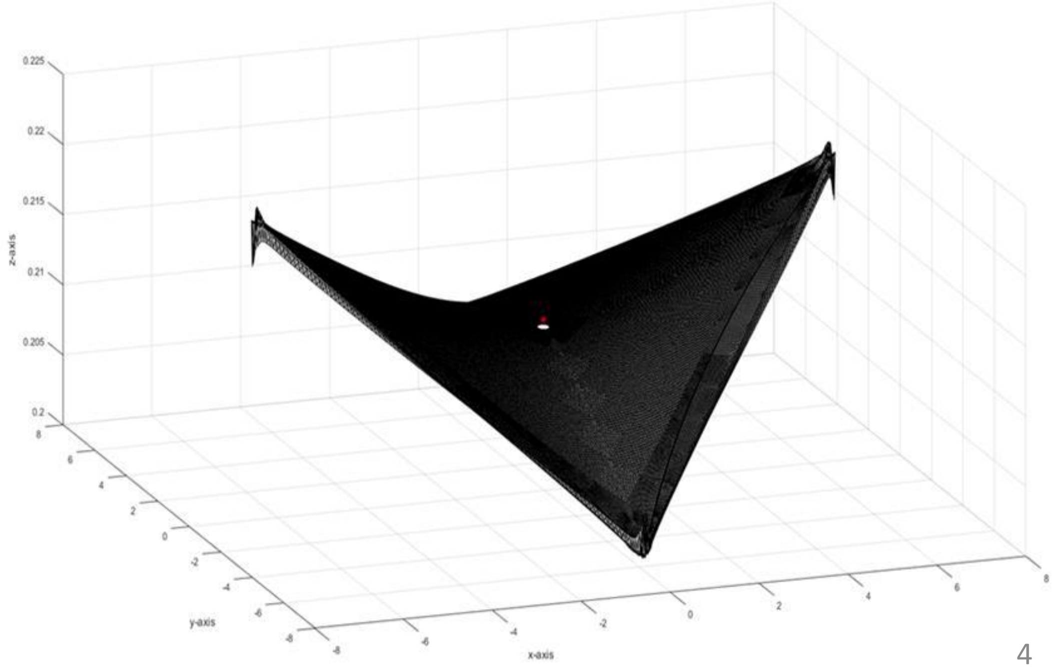


NEA Scout Control System



- 3D sail shape as predicted by finite element modeling
- Star tracker, Inertial Measurement Unit (IMU), sun sensors for attitude determination
- Reaction wheel (RW) control
- Active Mass Translator (AMT) and Reaction Control System (RCS) momentum management (MM)





Generalized Model for Solar Sails

- Torque due to arbitrary 3D sail shape
  - $\vec{M}_{\text{shape}} = p\left(a_2 \mathbf{K}^2 \cdot \hat{\mathbf{r}}_s - a_1 \hat{\mathbf{r}}_s \cdot \mathbf{K}^3 \cdot \hat{\mathbf{r}}_s - a_3 \hat{\mathbf{r}}_s \cdot \mathbf{L} \cdot \hat{\mathbf{r}}_s\right)$
  - ***<u>Torque tensors - 36 unique coefficients</u>***
    - $\mathbf{K}^2$, $\mathbf{K}^3$, $\mathbf{L}$
  - Unit sun vector in sail body frame, $\hat{\mathbf{r}}_s$
  - Solar pressure, p
  - Derived optical coefficients
    - $\mathrm{a}_1 = 2\mathrm{rs}$
    - $\mathrm{a}_2 = \frac{\mathrm{B_f}(1-\mathrm{s})\mathrm{r} + (1-\mathrm{r})(\mathrm{e_f B_f} - \mathrm{e_b B_b})}{\mathrm{e_f} + \mathrm{e_b}}$
    - $\mathrm{a}_3 = 1 - \mathrm{rs}$
- Torque due to force and center of mass (CM)
  - $\vec{M}_{\text{force}} = -\vec{\mathbf{r}}_{\text{cm}} \times \vec{f}_{sail}$
- L. Rios-Reyes and D. J. Scheeres, Generalized Model for Solar Sails, Journal of Spacecraft and Rockets Vol. 42 No. 1 (2005) 182-185.

Torque Model Characterization

- Least squares problem
  - $\boldsymbol{A}\,\boldsymbol{x} = \boldsymbol{b}$
  - $\boldsymbol{x} \equiv \boldsymbol{K} = \begin{matrix} [K_{1,1}^2\ K_{1,2}^2\ K_{1,3}^2\ K_{2,1}^2\ K_{2,2}^2\ K_{2,3}^2\ K_{3,1}^2\ K_{3,2}^2\ K_{3,3}^2\ \dots \\ K_{1,1,1}^3\ K_{1,1,2}^3\ K_{1,1,3}^3\ K_{1,2,2}^3\ K_{1,2,3}^3\ K_{1,3,3}^3\ \dots \\ K_{2,1,1}^3\ K_{2,1,2}^3\ K_{2,1,3}^3\ K_{2,2,2}^3\ K_{2,2,3}^3\ K_{2,3,3}^3\ \dots \\ K_{3,1,1}^3\ K_{3,1,2}^3\ K_{3,1,3}^3\ K_{3,2,2}^3\ K_{3,2,3}^3\ K_{3,3,3}^3\ \dots \\ L_{1,1}\ L_{1,2}\ L_{1,3}\ L_{2,1}\ L_{2,2}\ L_{2,3}\ L_{3,1}\ L_{3,2}\ L_{3,3}]^T \end{matrix}$
  - $\boldsymbol{b} \equiv \vec{\boldsymbol{M}}_{shape}/p$
    - $\vec{\boldsymbol{M}}_{shape} = \vec{\boldsymbol{M}}_{total} - \vec{\boldsymbol{M}}_{force}$
    - $\vec{\boldsymbol{M}}_{total}$ found from reaction wheel telemetry
    - $\vec{\boldsymbol{M}}_{force}$ calculated from sail force model and AMT position telemetry
- L. Rios-Reyes and D. J. Scheeres, Solar-Sail Navigation: Estimation of Force, Moments, and Optical Parameters, Journal of Guidance, Control, and Dynamics Vol. 30 No. 3 (2007) 660-668.

- $\boldsymbol{A}$ satisfies
  - $\vec{\boldsymbol{M}}_{shape}/p = \mathbf{A} \cdot \boldsymbol{K}$
  - Solved from tensor equation using the Maxima computer algebra system
  - Calculated using sun vector at each torque measurement
- For *m* torque measurements:
  - $\boldsymbol{b} = \begin{bmatrix} \boldsymbol{b}_1 \\ \dots \\ \boldsymbol{b}_m \end{bmatrix}$
  - $\boldsymbol{A} = \begin{bmatrix} \boldsymbol{A}_1 \\ \dots \\ \boldsymbol{A}_m \end{bmatrix}$

$$\mathbf{A}_{\mathrm{m}}^{\mathrm{T}} = \begin{bmatrix} r_1 a_2 & 0 & 0 \\ a_2 r_2 & 0 & 0 \\ a_2 r_3 & 0 & 0 \\ 0 & r_1 a_2 & 0 \\ 0 & a_2 r_2 & 0 \\ 0 & a_2 r_3 & 0 \\ 0 & 0 & r_1 a_2 \\ 0 & 0 & a_2 r_2 \\ 0 & 0 & a_2 r_3 \\ -a_1 r_1 & 0 & 0 \\ -2a_1 r_1 r_2 & 0 & 0 \\ -2a_1 r_1 r_3 & 0 & 0 \\ -a_1 r_2 & 0 & 0 \\ -2a_1 r_2 r_3 & 0 & 0 \\ -a_1 r_3 & 0 & 0 \\ 0 & -a_1 r_1 & 0 \\ 0 & -2a_1 r_1 r_2 & 0 \\ 0 & -2a_1 r_1 r_3 & 0 \\ 0 & -a_1 r_2 & 0 \\ 0 & -2a_1 r_2 r_3 & 0 \\ 0 & -a_1 r_3 & 0 \\ 0 & 0 & -a_1 r_1 \\ 0 & 0 & -2a_1 r_1 r_2 \\ 0 & 0 & -2a_1 r_1 r_3 \\ 0 & 0 & -a_1 r_2 \\ 0 & 0 & -2a_1 r_2 r_3 \\ 0 & 0 & -a_1 r_3 \\ 0 & r_1 a_3 r_3 & -r_1 r_2 a_3 \\ -r_1 a_3 r_3 & 0 & r_1\ a_3 \\ r_1 r_2 a_3 & -r_1\ a_3 & 0 \\ 0 & r_2 a_3 r_3 & -r_2\ a_3 \\ -r_2 a_3 r_3 & 0 & r_1 r_2 a_3 \\ r_2\ a_3 & -r_1 r_2 a_3 & 0 \\ 0 & a_3 r_3 & -r_2 a_3 r_3 \\ -a_3 r_3 & 0 & r_1 a_3 r_3 \\ r_2 a_3 r_3 & -r_1 a_3 r_3 & 0 \end{bmatrix}$$

Sail Characterization Process

- Hold different inertial attitudes to collect telemetry
  - Time, RW speeds, attitude, AMT position
- Calculate total momentum & torque from RW speeds
  - Use RW inertia & alignment
  - Fit polynomials to smooth & reduce data set
- Calculate sail frame sun vector
  - Use ephemeris & attitude
- Calculate sail shape torque
  - Subtract torque from solar force & CM
  - Use force model, mass model, & AMT position
- Normalize by solar pressure
  - Calculate from solar flux & ephemeris
- Construct & solve least squares problem for torque coefficients

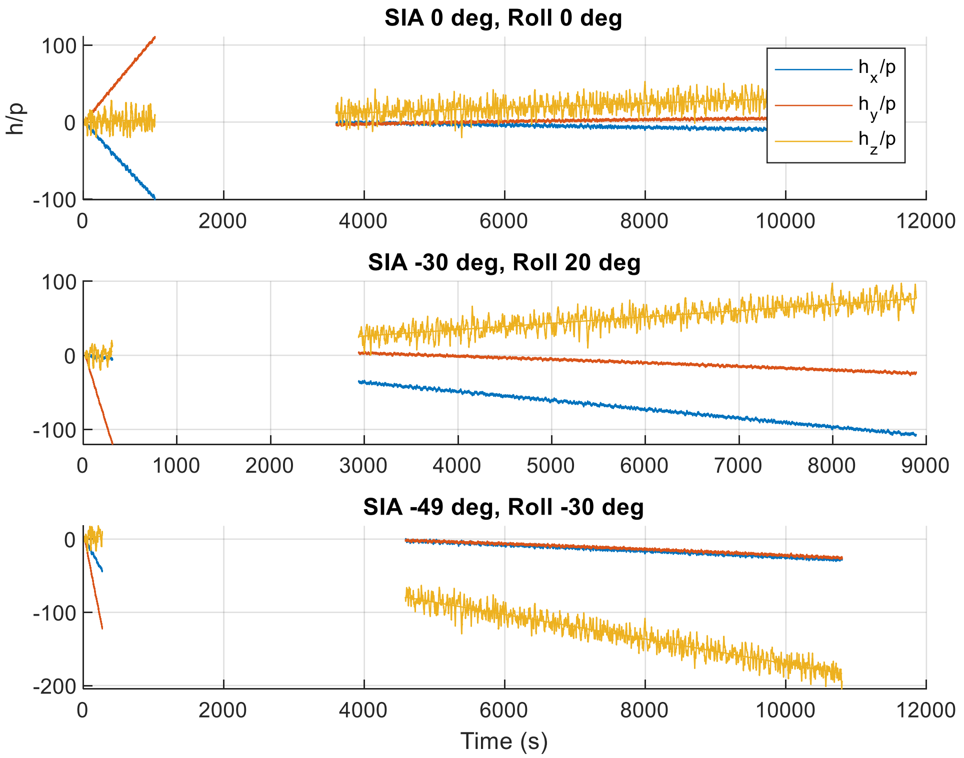
Sail Characterization Concept of Operations

- Hold Sun Incidence Angle (SIA) 0, Roll 0
- Increment by 10 deg SIA
- Roll between +/- 30 deg
  - 30 deg steps at 10 deg SIA
    - Less sensitive to roll changes
  - 10 deg steps at higher SIA
- Step to next attitude during comm window
- Retreat to previous safe attitude if problems encountered

SIA (deg)	Roll (deg)
0	0
10	0
10	+30
10	-30
20	-30
20	-20
…	…
20	+30
30	+30
…	…
30	-30
…	…
49	-30

Simulation

- Simulation of NEA Scout at each attitude for 3 hours
- Primary telemetry is RW speeds
  - Fit polynomials to find momentum as function of time
  - Polynomial derivatives for torque as function of time



Body frame wheel momentum / solar pressure

Results - Torque Coefficients

- Substantial absolute and relative errors between plant model (truth) coefficients and those found using least-squares
- Potential causes
  - Limited range of angles
  - Full number of coefficients to converge on with limited angles
- How well do they reproduce plant model torques?

$$\mathbf{L}_{est} = \begin{bmatrix} -0.0805 & -0.0122 & 0.0030 \\ 0.0035 & -0.0453 & 0.0043 \\ 0.0022 & 0.6433 & 0.1258 \end{bmatrix}$$

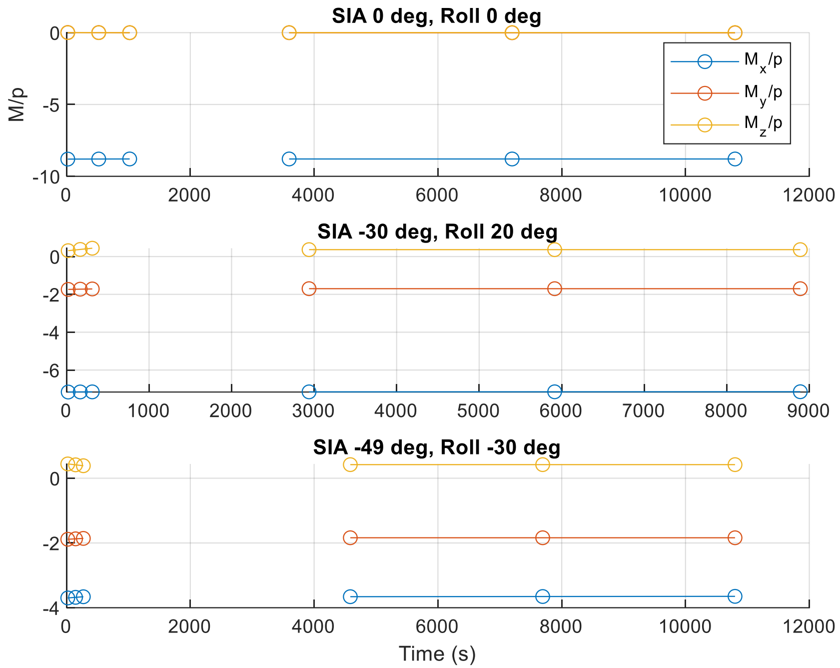
$$\mathbf{L}_{plant} = \begin{bmatrix} -0.2476 & -0.0009 & -0.0012 \\ -0.0025 & 0.2328 & -0.0050 \\ 0.0002 & 4.9006 & 18.2043 \end{bmatrix}$$

$$\mathbf{L}_{plant} - \mathbf{L}_{est} = \begin{bmatrix} -0.1671 & 0.0113 & -0.0042 \\ -0.0060 & 0.2781 & -0.0094 \\ -0.0020 & 4.2574 & 18.0785 \end{bmatrix}$$

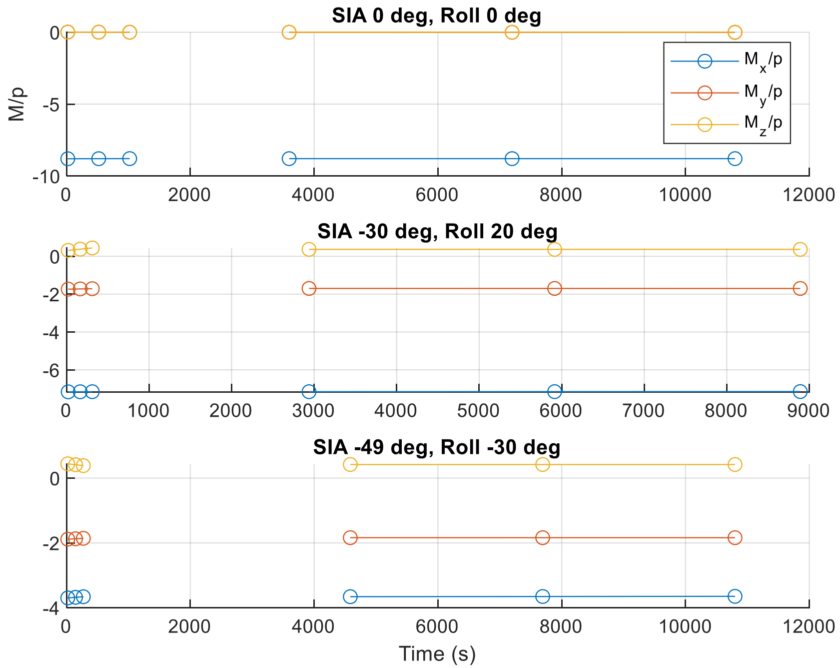
$$\frac{\mathbf{L}_{plant} - \mathbf{L}_{est}}{\mathbf{L}_{plant}} = \begin{bmatrix} 0.6749 & -12.9956 & 3.4897 \\ 2.4004 & 1.1948 & 1.8648 \\ -10.7889 & 0.8687 & 0.9931 \end{bmatrix}$$

Results - Torque Polynomials

- Total torque polynomial values

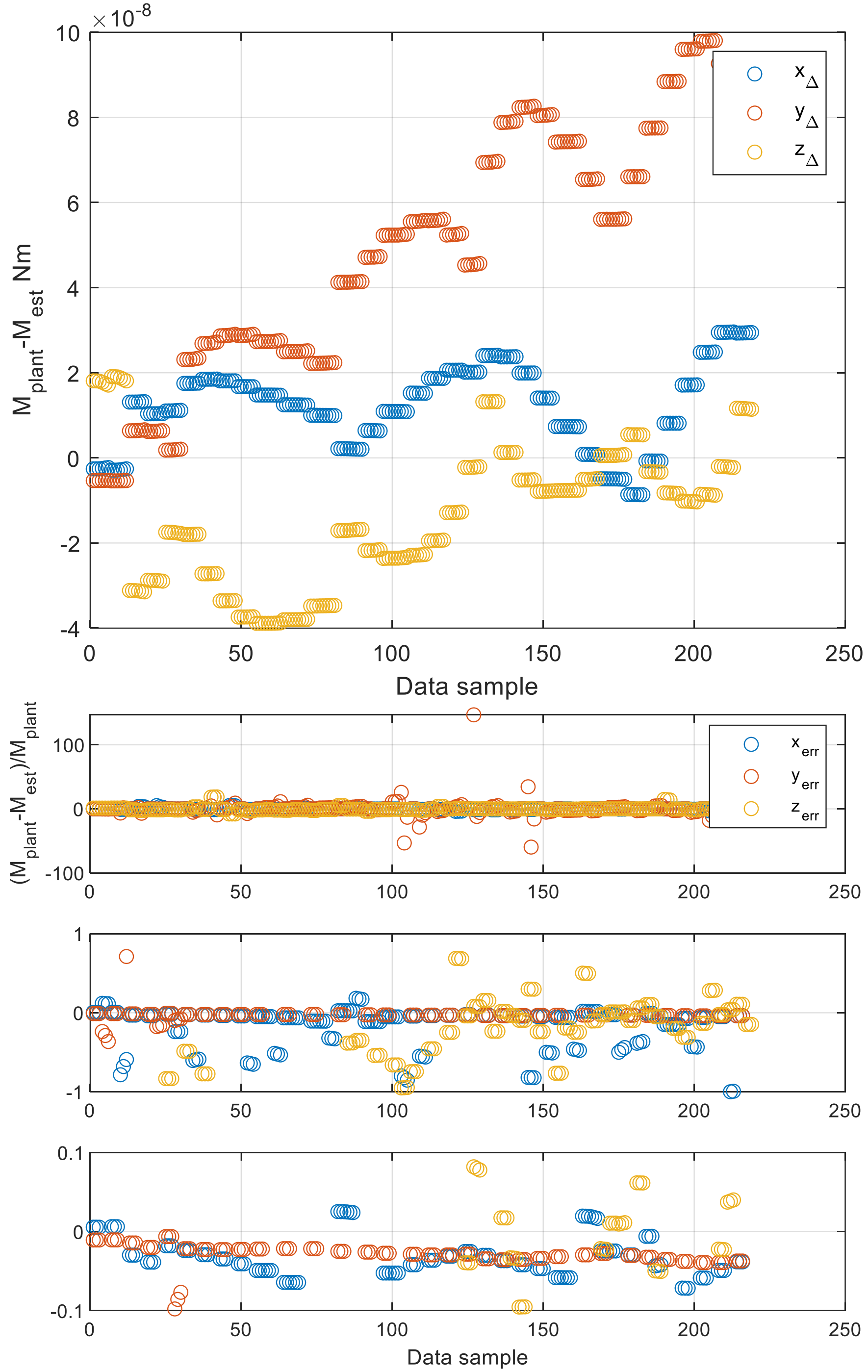


- Sail shape torque polynomial values



Results - Torques

- Compared plant model torques to estimated model torques
  - With same inputs as simulation
- Absolute torque differences within 10^{-8} Nm
  - At some samples truth torque may be within this noise floor
- Relative torque differences
  - Many data samples within
    - 5% Y
    - 10% X
    - 100% Z
  - Larger outliers
- Results promising (in X and Y) with room for improvement



Conclusions

- Took the theoretical torque characterization process from Rios-Reyes & Scheeres and implemented it for NEA Scout using detailed G&C simulation to test processing representative telemetry
- Results are promising, with large relative errors in many of the measurements
- Room to improve process

Future Work

- Study improvements to process
  - Rejection of measurements that fall within noise floor
  - Test enlarging the range of attitudes
    - Cloverleaf pattern identified by Rios-Reyes & Scheeres
  - Reduce set of coefficients being solved for using symmetry assumptions
  - Analyze noise sources in different axes and how to mitigate them
  - Tolerance of control system design to errors in torque model
- Apply process to other missions
  - ACS3
    - Low Earth Orbit; no AMT; aero, gravity gradient, & Earth radiative torques
  - Solar Cruiser
    - Lagrange orbit trajectory; AMT with full range of motion
  - Others?