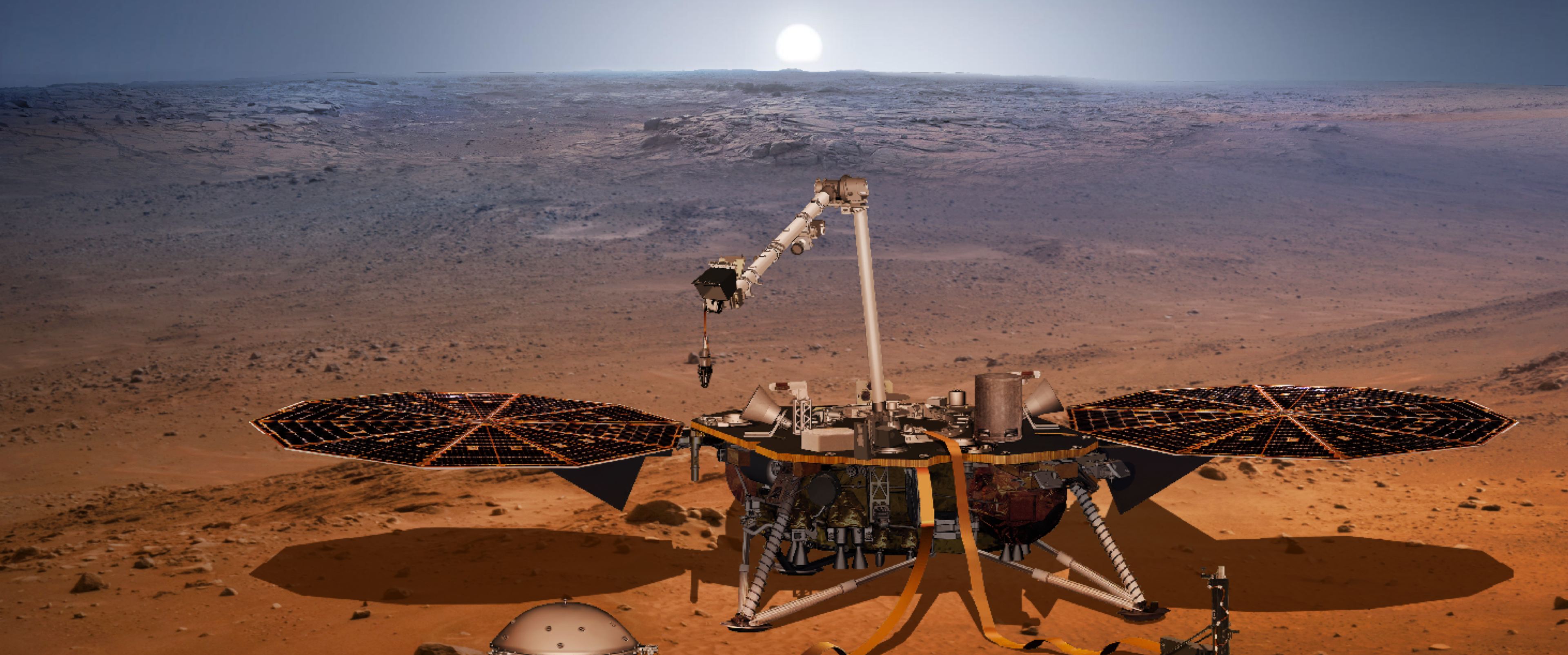

InSight Attitude Control System Thruster Characterization and Calibration for Successful Navigation to Mars

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Introduction

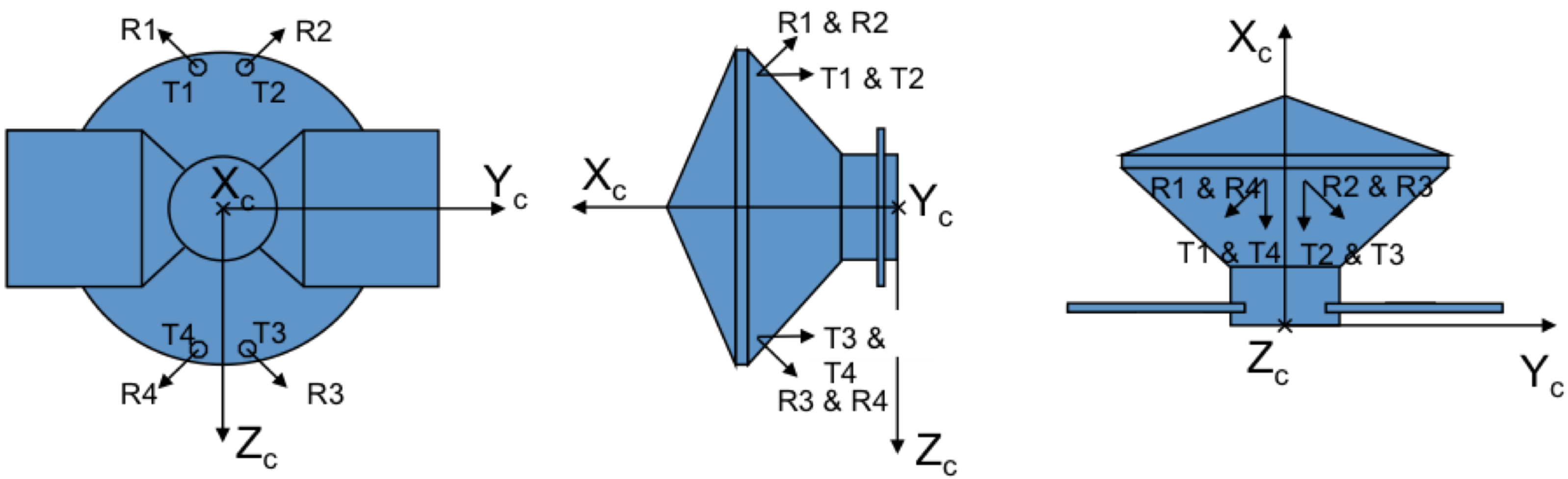
- InSight carried significant heritage from 2007 Phoenix Lander – including unbalanced Reaction Control System (RCS) thrusters used for attitude control

- Proper in-flight characterization of thruster firings (small forces) historically significant for Mars exploration
  - e.g. 2001 Mars Odyssey, 2005 MRO, 2007 Phoenix Lander
  - Loss of 1999 MCO

- Accumulation of ~ 29,000 RCS thruster firings over 7 month cruise significant impacted spacecraft trajectory
  - Accurate reconstruction and prediction of RCS thruster firings was crucial for successful delivery to atmospheric entry point

Attitude Control System (ACS)

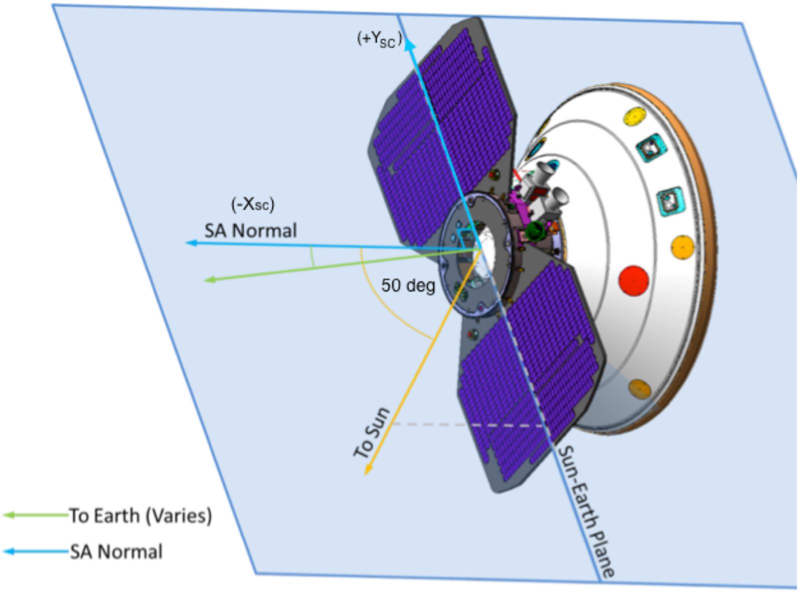
- Attitude control provided via an unbalanced thruster system
  - 4 Reaction Control System (RCS) thrusters fire in pairs for 3-axis stabilization & slew to/from TCM attitudes
- 4 Trajectory Correction Maneuver (TCM) thrusters execute main burns
- RCS/TCM thrusters mounted onto lander & extended through backshell
  - Scarfed to backshell contour
  - Each RCS thrust vector had non-zero component in all 3 axes



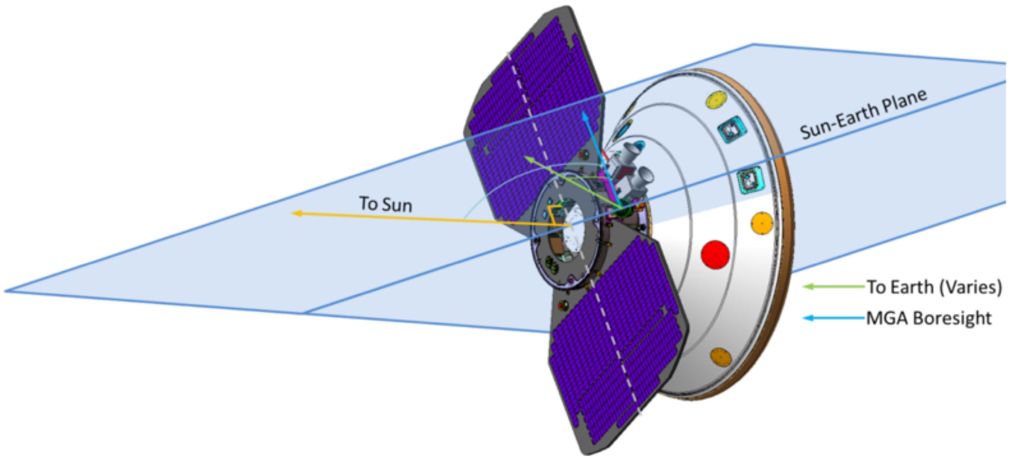
Cruise Attitude Profiles

- Two attitude profiles designed to balance power, communications, and thermal constraints throughout cruise

Early Cruise: Launch to July 12



Late Cruise: July 12 to Entry



- Early cruise: 3-axis RCS ΔV due to off-Sun pointing
- Late cruise: Y and Z nominally balanced, RCS ΔV in X direction
  - In reality, thrusters not perfectly balanced, small ΔVs in Y and Z also

Attitude Deadband Constraints

- Nominal cruise attitudes maintained via deadbanding
  - Attitude allowed to drift through 3-D deadband
  - RCS thrusters fired when a deadband limit was reached

- Early and late cruise deadbands defined to cover Earth/Sun/Spacecraft geometry variation
  - Tighter deadband constraints resulted in more frequent thruster firings
    - Imparted ΔV increased after late cruise transition

Table 1. Spacecraft Attitude Deadband Definitions (Spacecraft-Fixed Frame)

Cruise Phase	X	Y	Z
Early Cruise (May 5, 2018 to July 12, 2018)	10°	10°	7.5°
Late Cruise (July 12, 2018 to November 26, 2018)	4°	4°	4°

ACS Telemetry

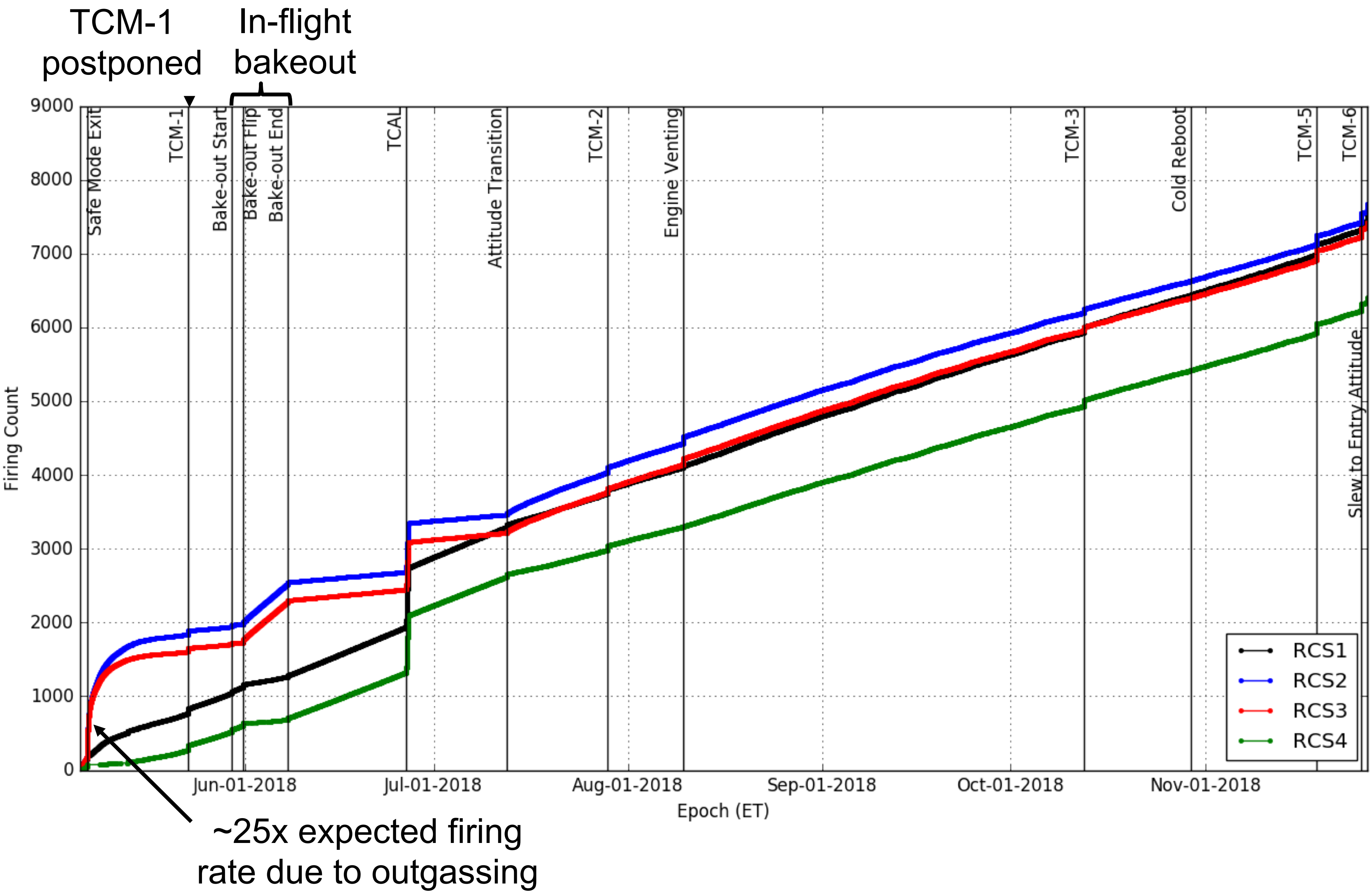
- Attitude knowledge via star trackers, MIMUs, Sun sensors (backup)

- Raw telemetry packet recorded with every RCS/TCM thruster pulse
  - Thruster on time
  - Pulse length
  - Thruster number
  - On-board estimated ΔV & quaternions at time of firing

- Raw telemetry used to construct *a priori* models of small forces and attitude for orbit determination (OD) and trajectory prediction

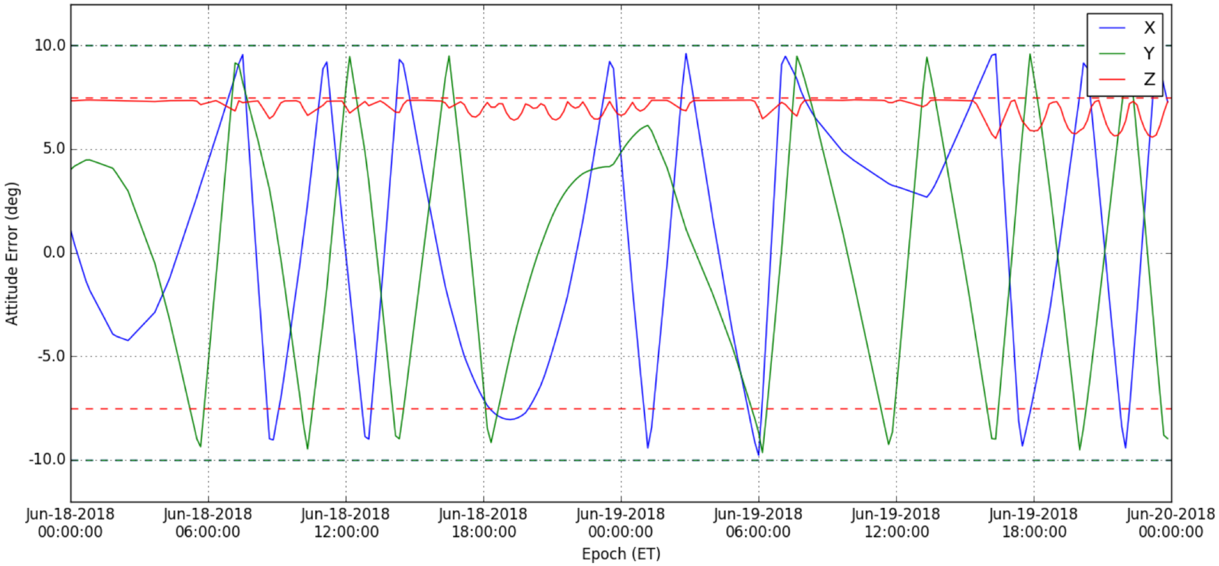
- On-board filtered telemetry used during Thruster Calibration analysis

RCS Thruster Flight Performance

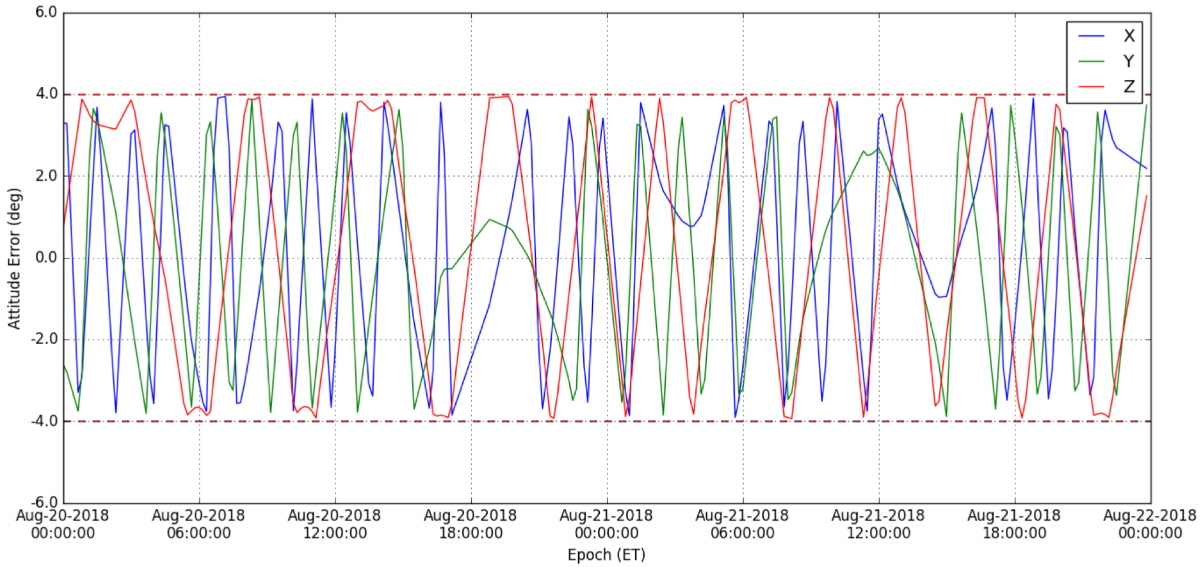


Attitude Errors During Nominal Cruise Ops

- Early cruise:
  - Solar torque due to off-Sun pointing pinned spacecraft against +Z deadband
  - Drifts between ±X and ±Y limits

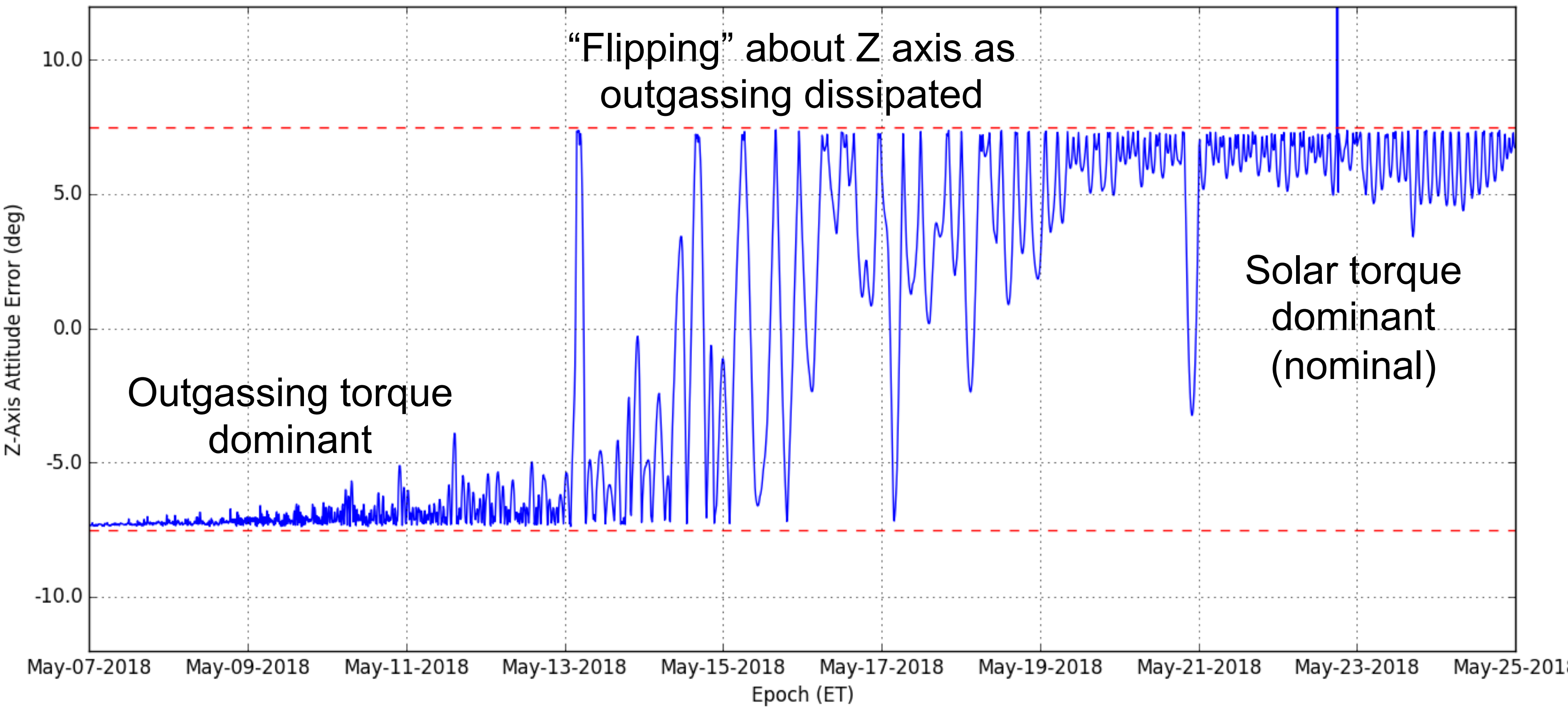


- Late cruise:
  - Solar torque balanced as solar arrays ~ Sun-pointed
  - Drifts between ±X, ± Y, ± Z limits



Attitude Errors During Heavy Outgassing (May 2018)

- Outgassing torque pinned spacecraft against the -Y, -Z deadbands
- Outgassing and solar pressure torques acted in opposite directions
  - Solar torque effect not observable until outgassing dissipated



Small Force Estimation

- OD strategy accounted for errors in small force telemetry
  - Reconstructed behavior of each individual RCS thruster
  - Improved upon Phoenix strategy (estimated accumulative effect of all RCS thrusters combined)
- ACS on-board telemetry used to model *a priori* attitude and ΔV at the time of each RCS thruster firing
  - Effective thrust vectors and imparted ΔV per firing based on:
    - Pre-TCAL: pre-launch models
    - Post-TCAL: estimated values
- Filter configured to estimate corrections to thruster models

Table 2. Baseline Small Force Estimation Strategy

Estimated Parameter (Per Thruster)	Model	*A Priori* Value	*A Priori* Uncertainty
Thrust Direction Y Offset	Bias	0°	3°
Thrust Direction Z Offset	Bias	0°	3°
ΔV Magnitude	Bias	0%	3%
ΔV Magnitude	White Noise Stochastic	0%	15%

Small Force Prediction

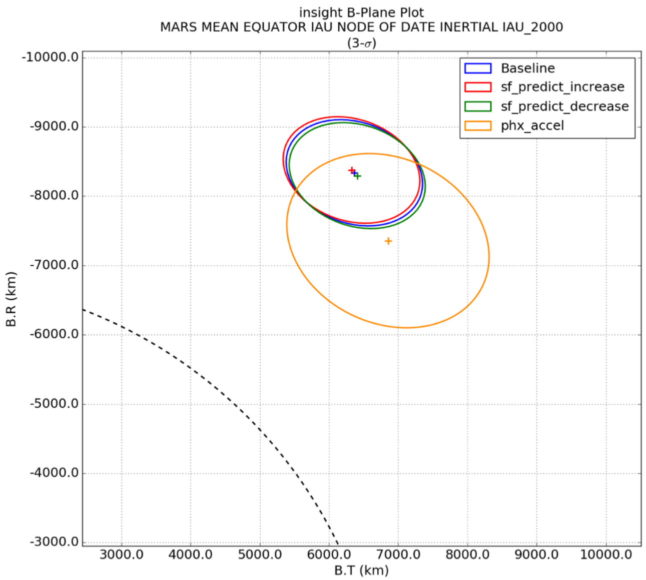
- Propagation of OD solution from data cut off to entry interface point included predictions of future small force behavior of each RCS thruster
  - Average acceleration empirically-determined via linear fit to recent firing counts
    - Linear firing rate computed for each thruster, converted to average acceleration using nominal thruster models
    - Nominal ΔV magnitude corrected based on estimated ΔV scale factor

- Effectively, on-going thruster characterization of short-term deadbanding behavior in response to varying astrodynamics conditions

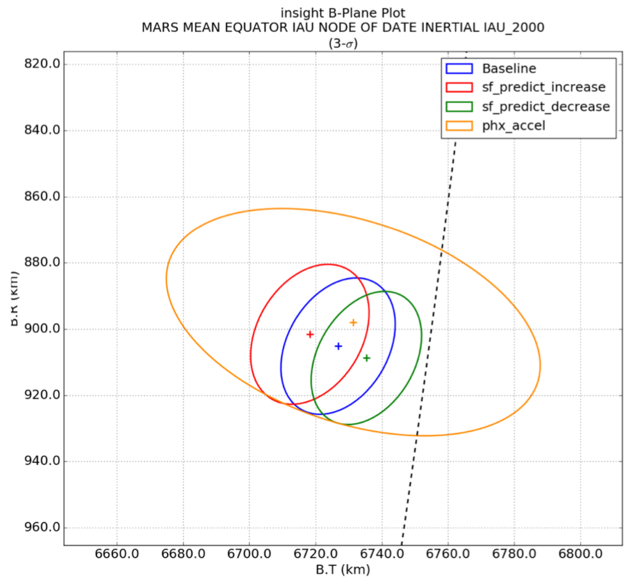
Small Force Model Comparisons

- Various predictive models compared throughout cruise to assess suitability of baseline approach
- Impact of small force prediction proportional to “time to go”

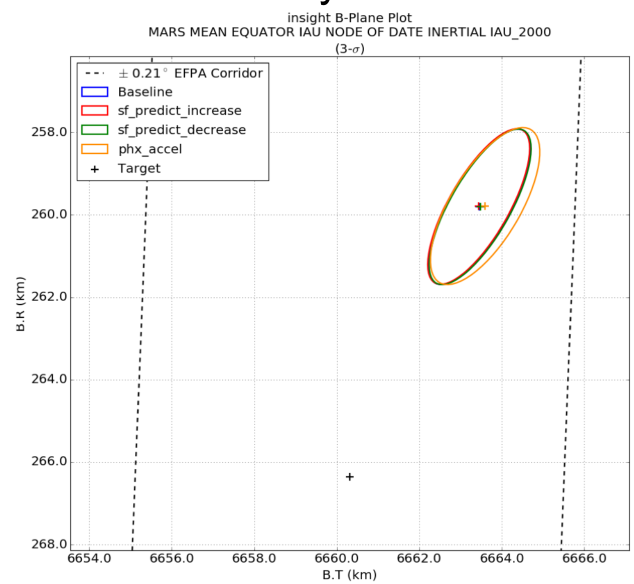
TCM-2 DCO
Entry-142 days



TCM-3 DCO
Entry-50 days



TCM-6 DCO
Entry-48 hrs



- Solution uncertainty driven by data uncertainties
- Phoenix model > 3**σ** away from baseline

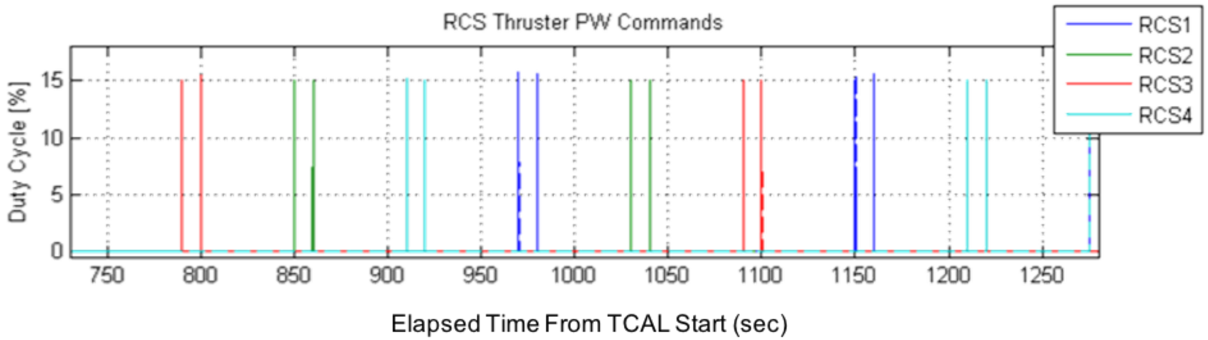
- Solution uncertainty driven by small force model
- ±5% acceleration shifts solution by 1**σ**

- Short propagation time renders models indistinguishable

Thruster Calibration Campaign: June 26, 2018

- Attempt to calibrate RCS thrusters in cruise environment via Thruster Calibration (TCAL)
  - Spacecraft rotated through four attitudes, sequence of thruster pulses ("pulse train") executed at each attitude
  - Pulse train executed 9x per attitude, attitude reset between executions
  - Attitudes selected to maximize line-of-sight observability, within safety constraints

- Pulse trains not representative to nominal deadbanding behavior
  - Thrusters fired much more frequently
  - Temperature-driven variations affect both direction and magnitude of thrust vector



Thruster Calibration Filter

- Objective: estimate linear impulse vector ($\vec{p}$) imparted by each thruster
- Multiple data streams utilized to enhance TCAL quality
  - Quaternion telemetry – 5 Hz
  - Angular rate ($\Delta\boldsymbol{\omega}$) telemetry – 5 Hz channelized, 50 Hz via MIMU
  - Doppler data - 1 Hz (data calibrated with OD solution to remove other dynamic/measurement errors)
- Data filtered to include only minimum impulse bit firings, to be more representative of nominal deadbanding
- Each pulse train filtered separately, combined in statistical batch sense

First constraint: angular momentum equation →

$$\Delta\vec{H} = I\Delta\vec{\omega} = \vec{r} \times \vec{p} = S(\vec{r})\vec{p}$$

Second constraint: linear momentum equation →

$$\vec{p} = m\Delta\vec{V}$$

$$\begin{bmatrix} S(\vec{r}) \\ \vec{l}^T \end{bmatrix} \vec{p} = \begin{bmatrix} I\Delta\vec{\omega} \\ m(\bar{l} \cdot \Delta\vec{V}) \end{bmatrix}$$

→ Fully-determined system to estimate $\vec{p}$

Thruster Calibration Results – Estimated Parameters

- Large offsets in thrust direction and magnitude scale factors estimated for each RCS thruster
  - Substantially larger than pre-launch uncertainties (3 degrees, 3%)

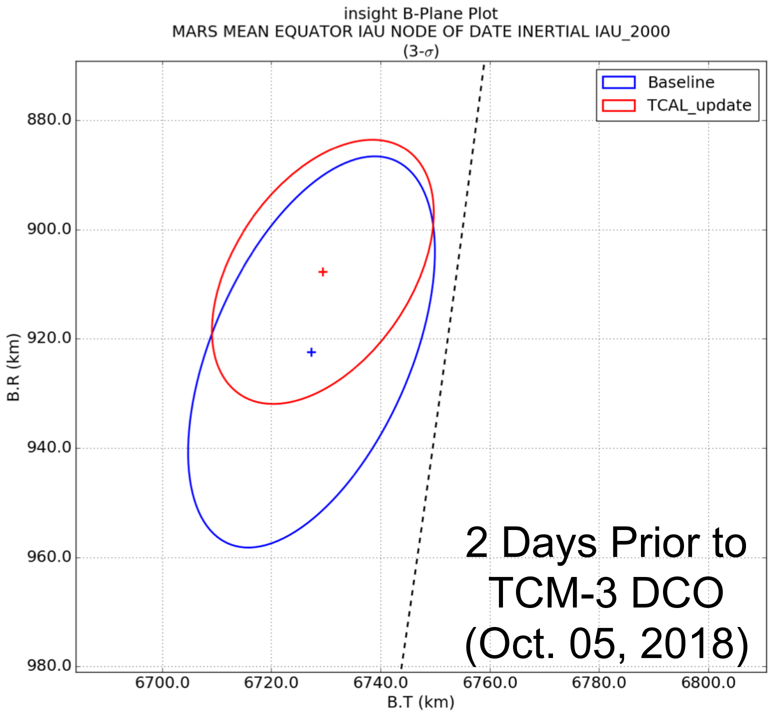
Table 4. Estimated Thruster Magnitude Scale Factor and Direction ([X, Y, Z])

	RCS1	RCS2
Nominal Direction	[0.3404, 0.7411, 0.5786]	[0.3652, -0.7571, 0.5417]
Estimated Direction	[0.4722, 0.7642, 0.4394]	[0.3610, -0.8002, 0.4790]
Estimated Direction Offset	11.08°	4.367°
Estimated Scale Factor	0.6738	0.7525
	RCS3	**RCS4**
Nominal Direction	[0.3707, -0.7661, -0.5251]	[0.3308, 0.7493, -0.5736]
Estimated Direction	[0.5176, -0.6997, -0.4925]	[0.4922, 0.7713, -0.4036]
Estimated Direction Offset	9.434°	13.52°
Estimated Scale Factor	0.6536	0.6900

- Applying estimated values to *a priori* OD filter models improved estimation of thrust magnitude, but not thrust direction
  - Filter still adjusts *a priori* directions by significant amount

Thruster Calibration Results – B-Plane Movement

- *A priori* thruster models updated from pre-launch to estimated values prior to TCM-3 DCO
  - No change to OD filter configuration
- *A priori* model change resulted in a 1σ shift in entry interface point, significant reduction in propagated solution uncertainty
  - Uncertainty proportional to estimated thrust magnitude scale factors



Summary

- Proper characterization of unbalanced RCS thrusters paramount to successful landing
- TCAL designed to optimize full thrust vector observability, but pulse trains not representative of nominal cruise deadbanding
  - Improved knowledge of thrust magnitude
  - Limited utility in thrust vector offset determination
- Empirical trending to recent small force telemetry combined with estimated corrections to nominal thruster models:
  - Produced stable and statistically consistent OD solutions
  - Predicted spacecraft trajectory exceptionally well

Acknowledgements

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  - The JPL Navigation Advisory Group for their guidance and advice.

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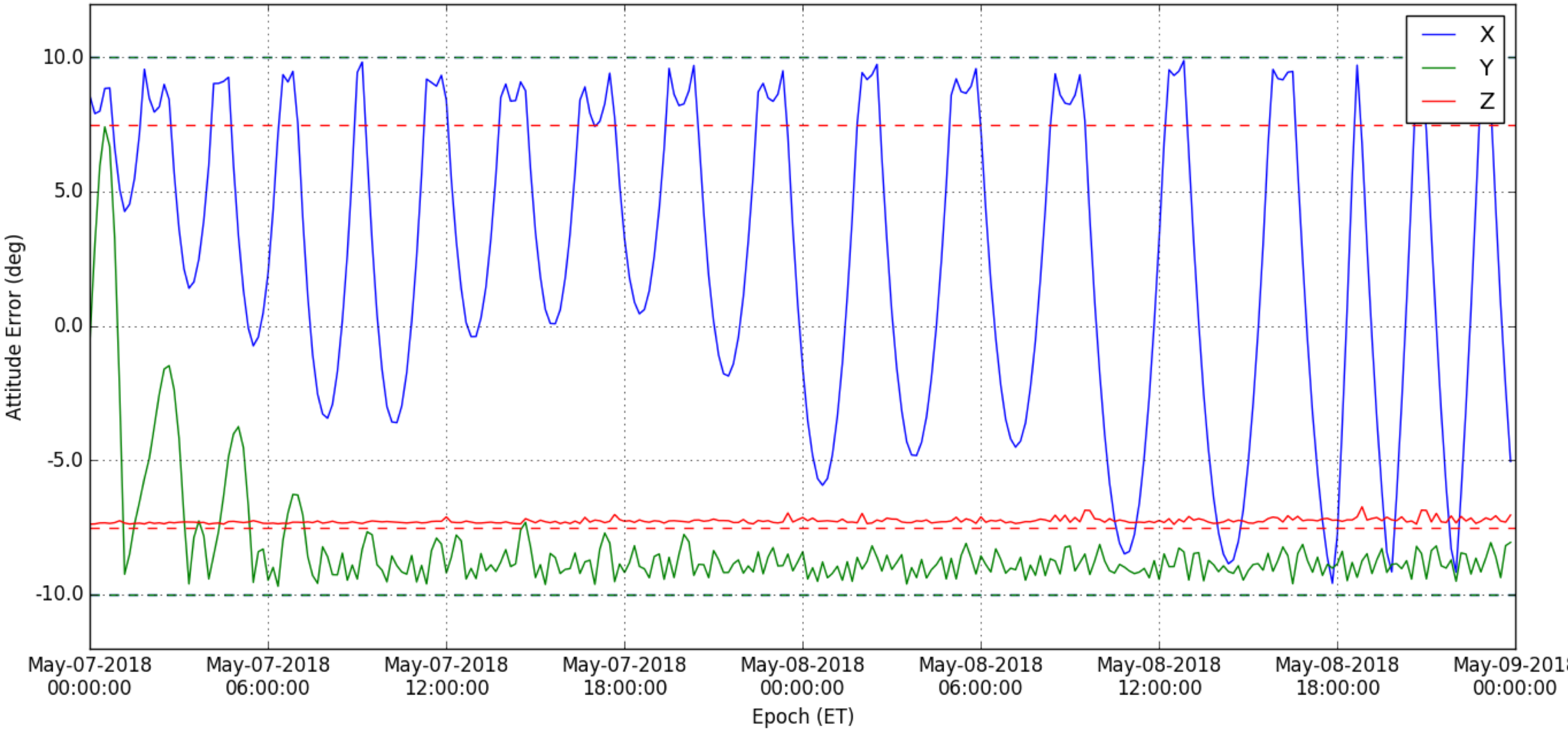
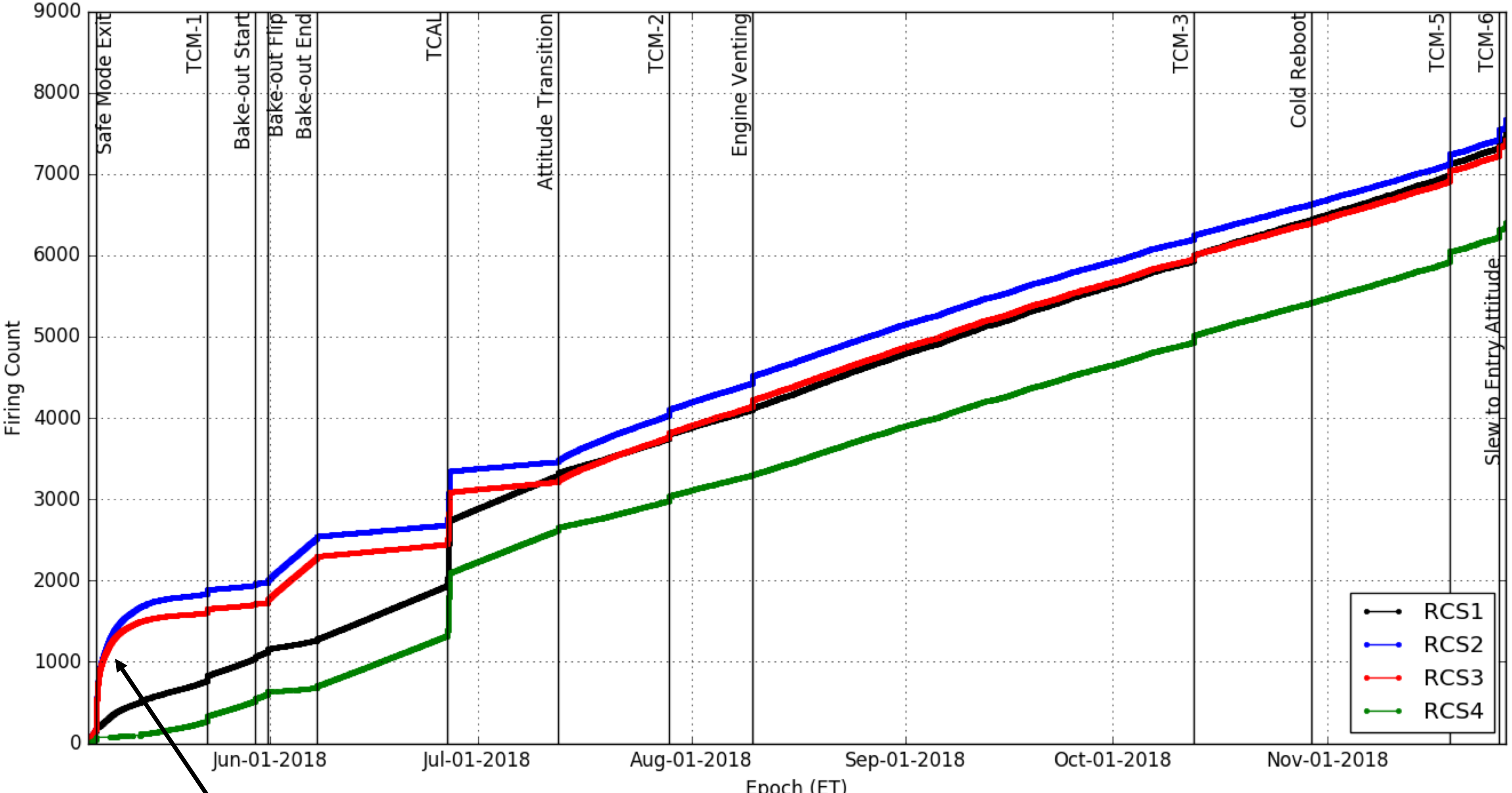
Backup - Attitude Errors During Heavy Outgassing



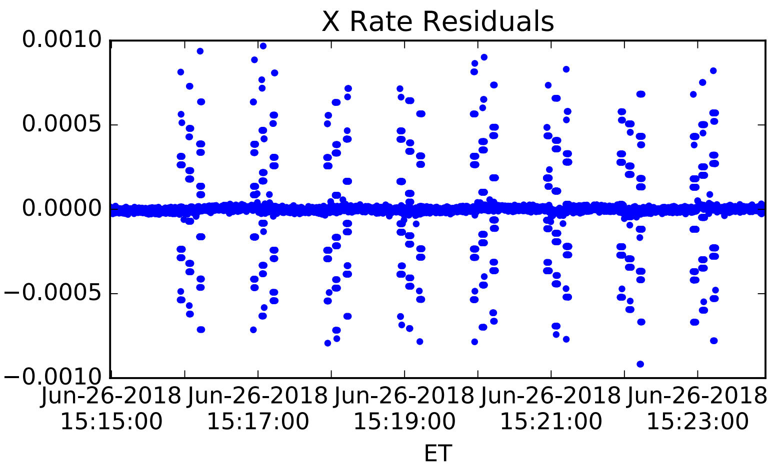
Small Force Empirical Prediction

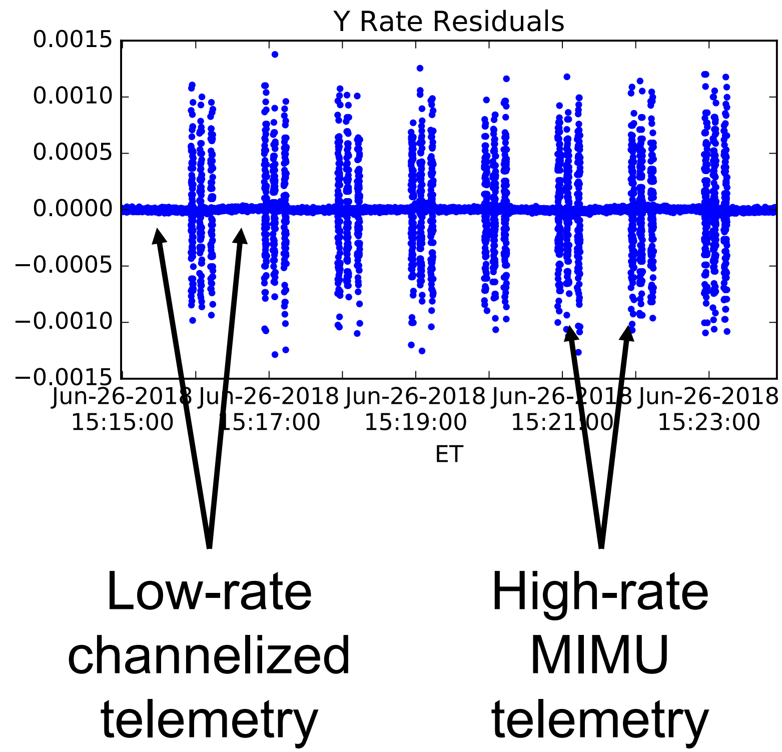
Daily variation < 0.5 mm/sec
over 1 day prediction

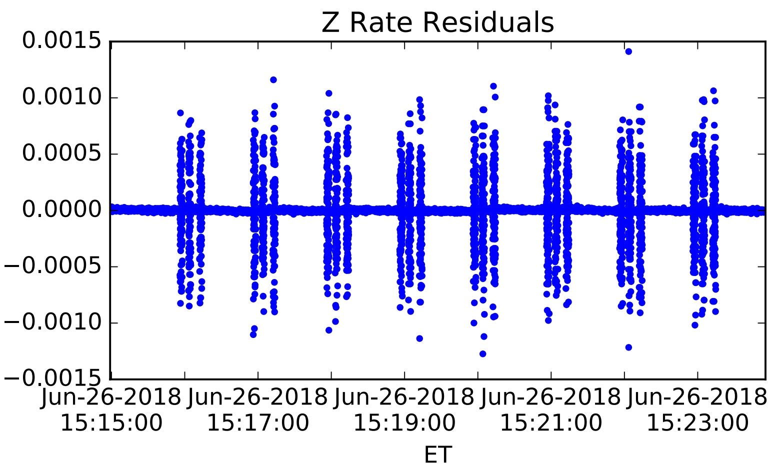


Significant variation in daily
predictions due to outgassing

Backup: TCAL Results – Angular Rate Postfit Residuals

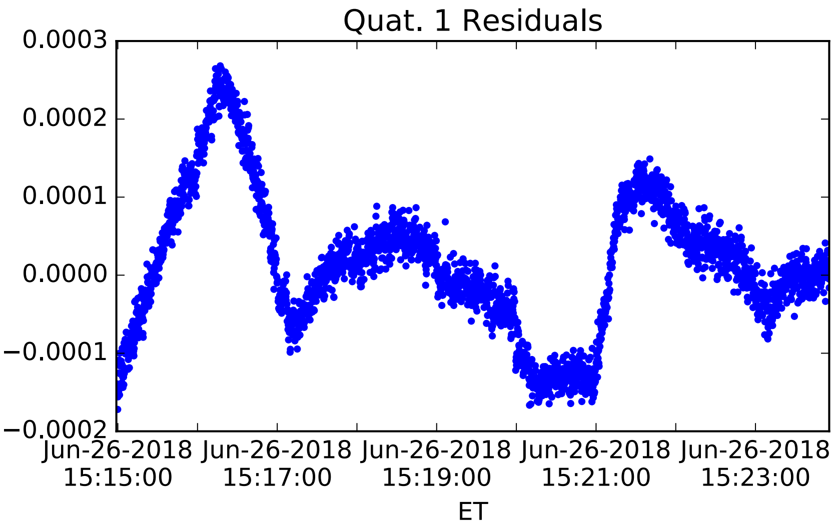


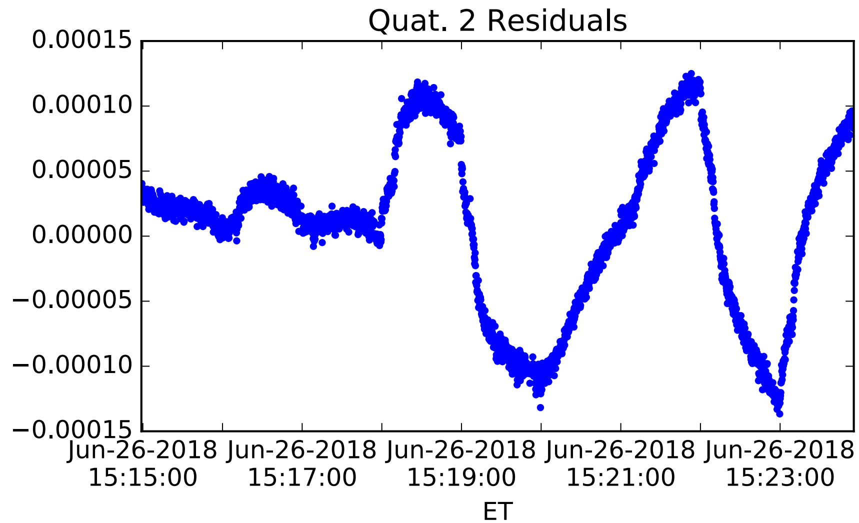


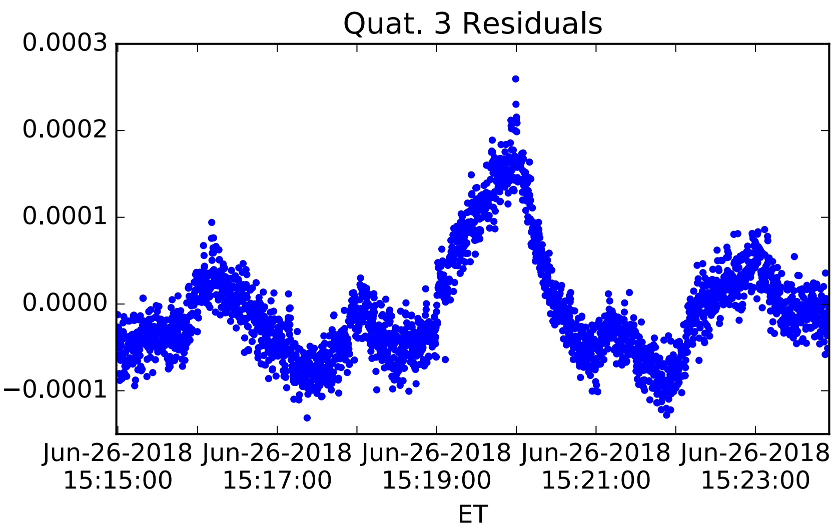


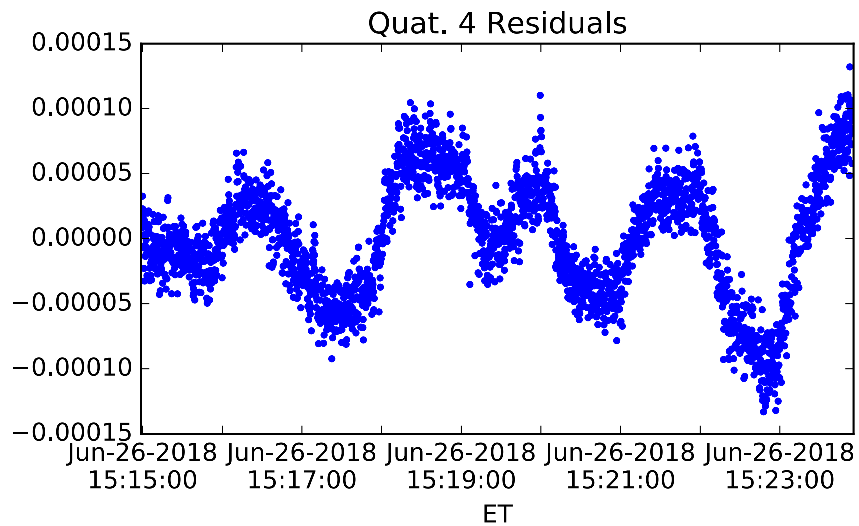
Backup: TCAL Results – Quaternion Postfit Residuals

- Systematic trends consistent with star tracker measurement errors









Backup: TCAL Results – LOS ΔV Postfit Residuals

- Statistically consistent with 2-way X-band Doppler