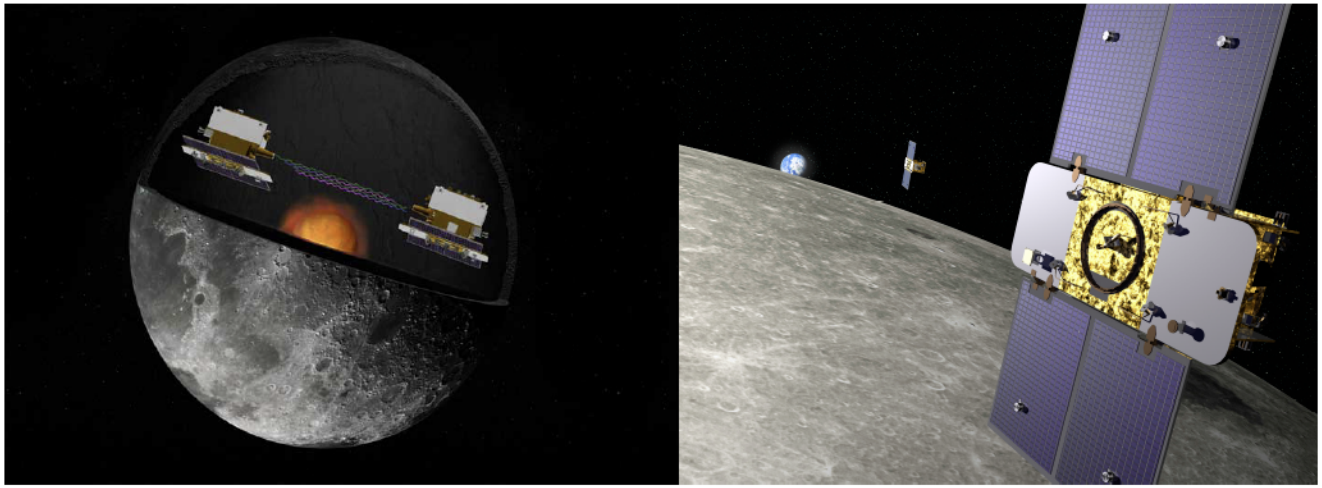
Gravity Recovery and Interior Laboratory (GRAIL) Orbit Determination



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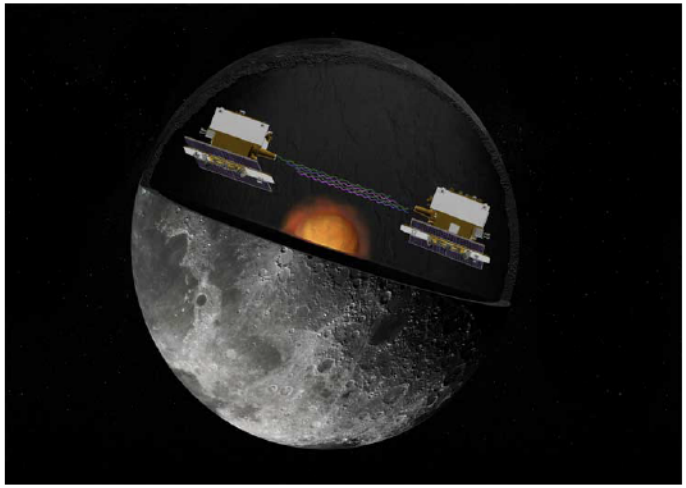
E. Higa, D. Jefferson, E. Lau, S. Mohan, M. Ryne, M. Keck

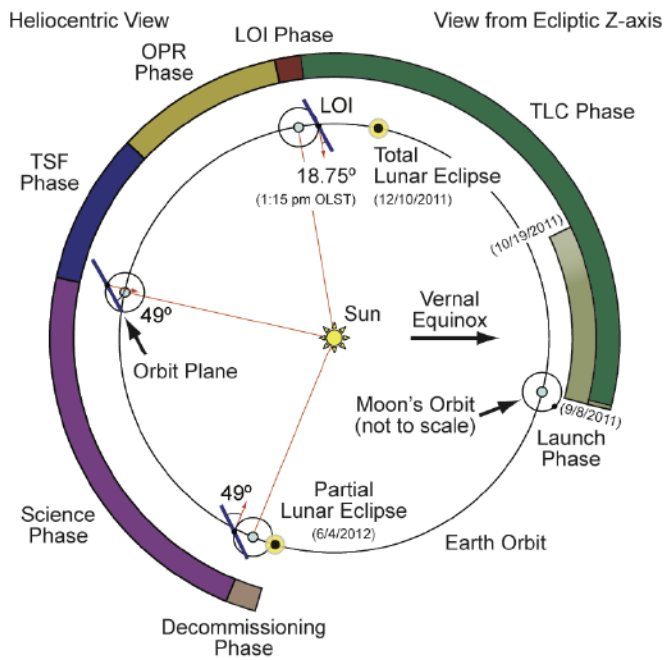
Jet Propulsion Laboratory
California Institute of Technology

23rd International Symposium on Space Flight Dynamics

Pasadena, California **29 Oct'12 – 02 Nov'12**

Mission Overview





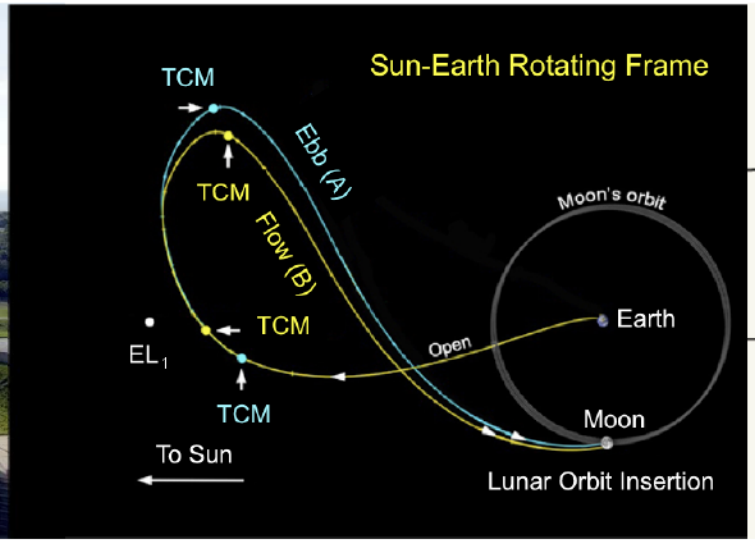
Primary Science Objectives

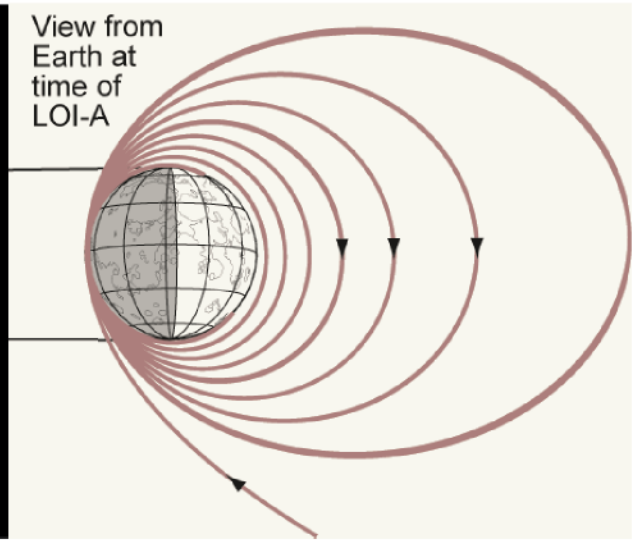
- **Interior Structure (Core)**
- **Thermal History**

9-month Primary Mission

- **3.5 Months Trans-lunar Cruise Phase (TLC)**
- **1 Week Lunar Orbit Insertion Phase (LOI)**
- **1 Month Orbit Period Reduction Phase (OPR)**
- **1 Month Transition to Science Formation Phase (TSF)**
- **3 Months Primary Science Phase**

Trajectory Design





Launch

- **Delta-II LV with Dual-SC Configuration**
- **42-day Launch Period**
- **2 Opportunities/Day**
- **Two Launch Azimuths**

TLC

- **Low-Energy Lunar Trajectory Design**
  - **5 TCMs (3 Deterministic) per S/C**
  - **Solar Pressure/Thruster Calibrations**

LOI

- **Separated by 1 day**
- **Capture into a 11.5hour Orbit Period**
- **~190 m/s burn**

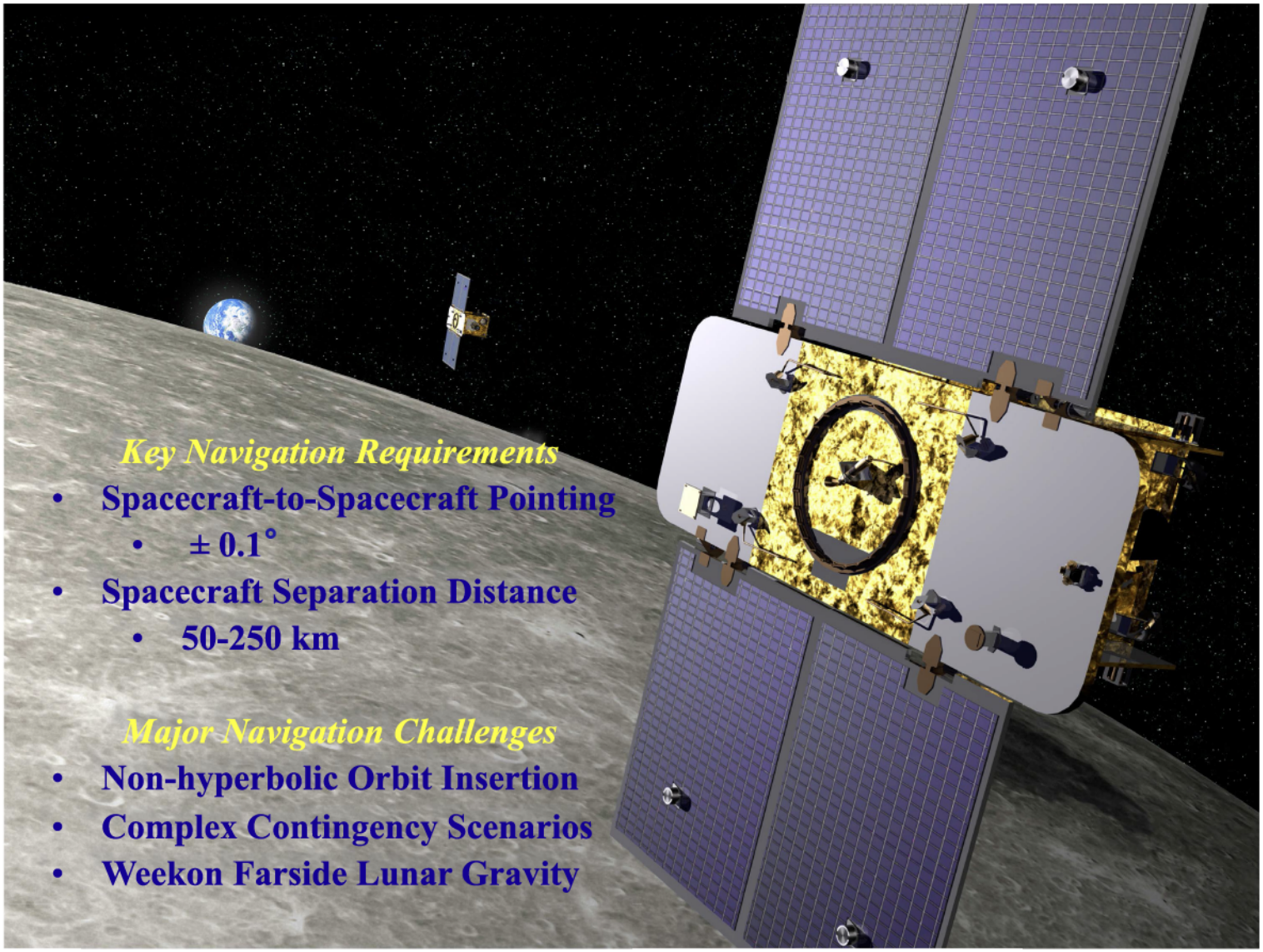
OPR

- **7 Maneuvers in Two Clusters for Each S/C**
- **Period reduced to ~ 2hours**

TSF

- **5 Maneuvers (2 As, 3Bs) to Establish Formation**

Navigation Challenges



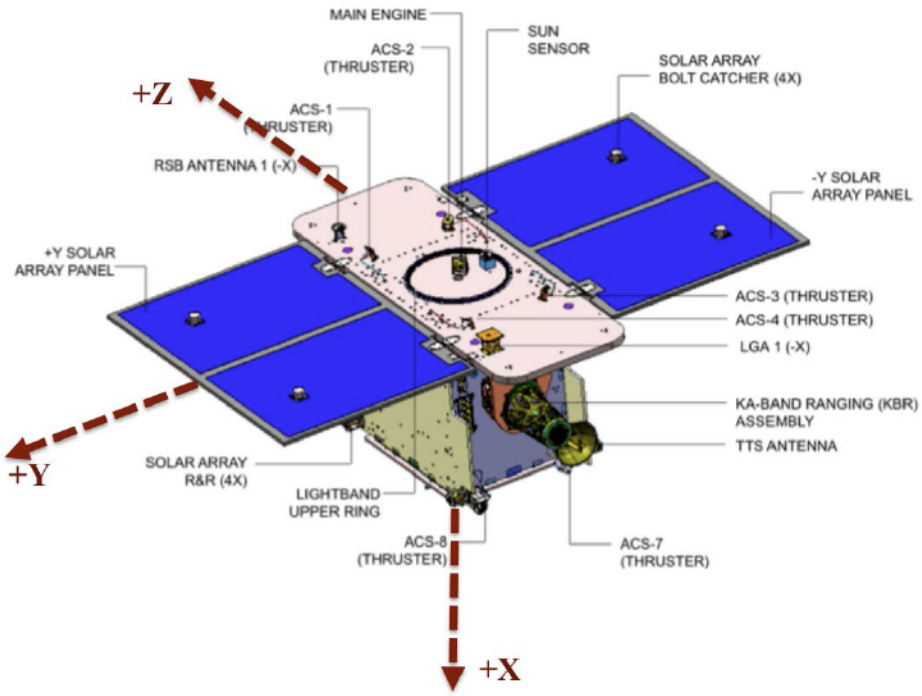
Key Navigation Requirements

- **Spacecraft-to-Spacecraft Pointing**
  - **± 0.1°**
- **Spacecraft Separation Distance**
  - **50-250 km**

Major Navigation Challenges

- **Non-hyperbolic Orbit Insertion**
- **Complex Contingency Scenarios**
- **Weekon Farside Lunar Gravity**

Spacecraft System



Specification	Thrust (N)	Number	Use
Main Engine MR-106	22.0	1	TCMs, PRM, TSM, LOI
Warm Gas ACS Thruster	0.9	8	Attitude Control, Desaturation, Small-size maneuvers

Spacecraft

- **Same Hardware Set**
- **Nearly Identical Configurations except:**
  - **Lunar Gravity Ranging System (LGRS)**
  - **Star Trackers**
  - **MoonKAMs**
- **S/C Body-fixed Coordinate System**
  - **Same definition for A & B**

Key Engineer Subsystems

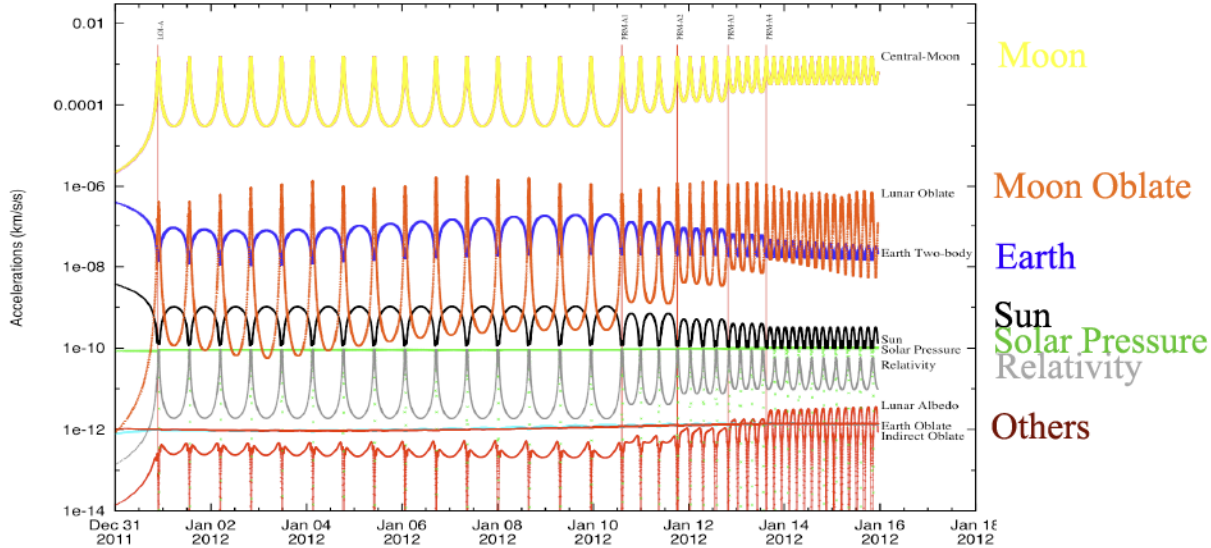
- **Propulsion and GN&C**
  - **3-axis Stabilized ACS**
  - **Blow-down Mode**
  - **1x 22N Main Engine**
  - **8 x 0.9N ACS Thrusters**
- **Telecommunication**
  - **Two Low-Gain Antennas**
  - **Two-way S-band**
  - **One-way X-band w/ USO**

Science Payloads

- **Ka-band LGRS**
- **MoonKAM**

Key Non-gravitational Dynamic Models

Major Forces In-Orbit



Gravity

- ***Earth Gravity: 20x20 GGM02C***
  - ***Spherical Influence On***
- ***Lunar Gravity: Full-Field LP150Q***
  - ***Spherical Influence On***
- ***Point Mass for the Sun, Planets***
- ***DE421 Planetary Ephemerides***
  - ***4 m (1σ) at arrival***

Solar Radiation Pressure

- **Reconstructed Quaternions w/ Background Attitude Profile**
- **8 Representative Components**

Thruster Activities

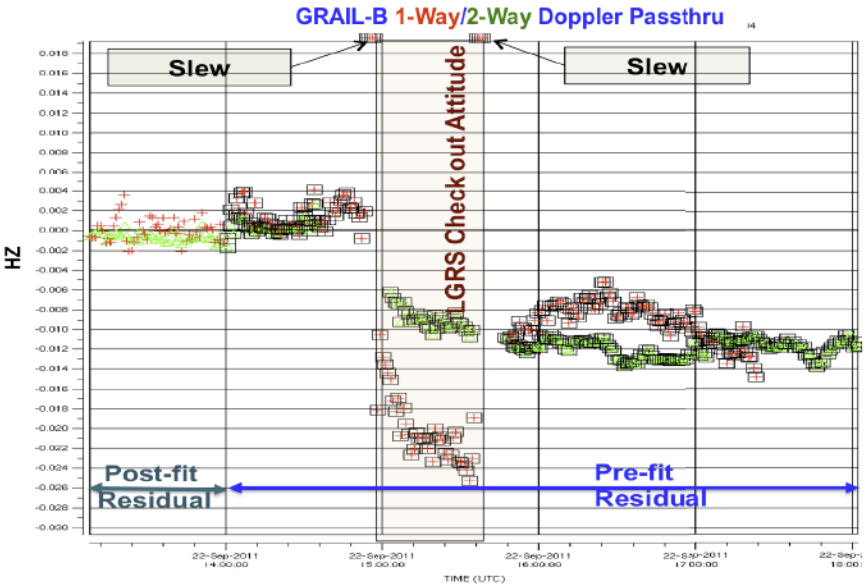
- **Propulsion Finite Burns**
- **Angular Momentum Desaturations**

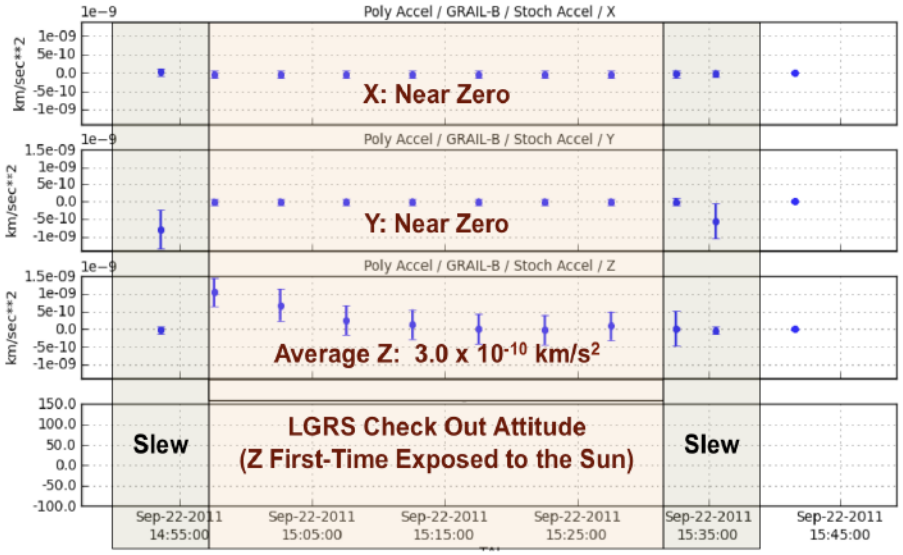
Outgassing

- ***Launch & Orientation Changes***

S/C Dynamics: Outgassing

Orbit Determination *GRAIL Navigation*





- **No significant Long-term Outgassing Found in Cruise Attitude**
  - **Depleted to a ~10^{-12} km/s^2 Level in a Few Days after the Launch**
  - **No Deterministic Model Was Included in the Predicted Trajectories**
- **Outgassing Events, at level of 10^{-9} km/s^2, Has Been Observed during Non-Cruise Attitudes**
  - **Does not have a long-term impact due to short durations**

Dynamic Model: Thruster Activities

Orbit Determination *GRAIL Navigation*

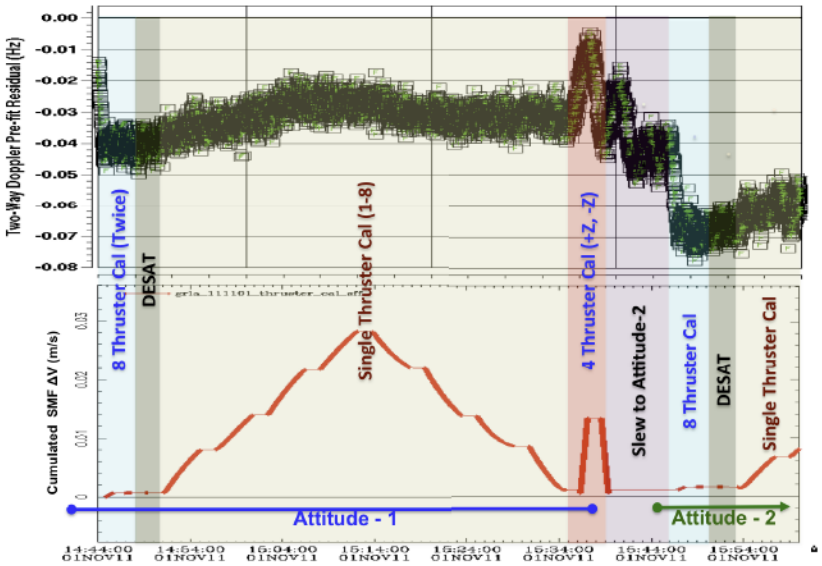
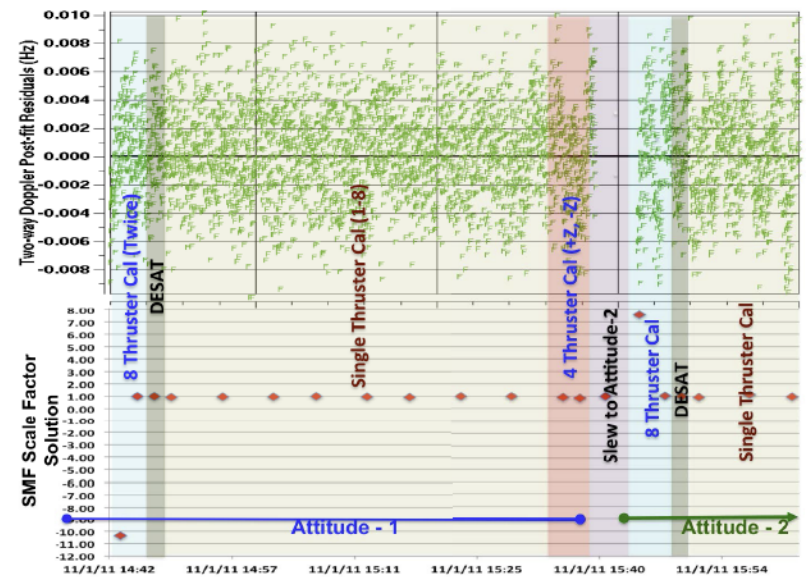


Table 1: Maneuver Timeline for the Science Orbit Establishment

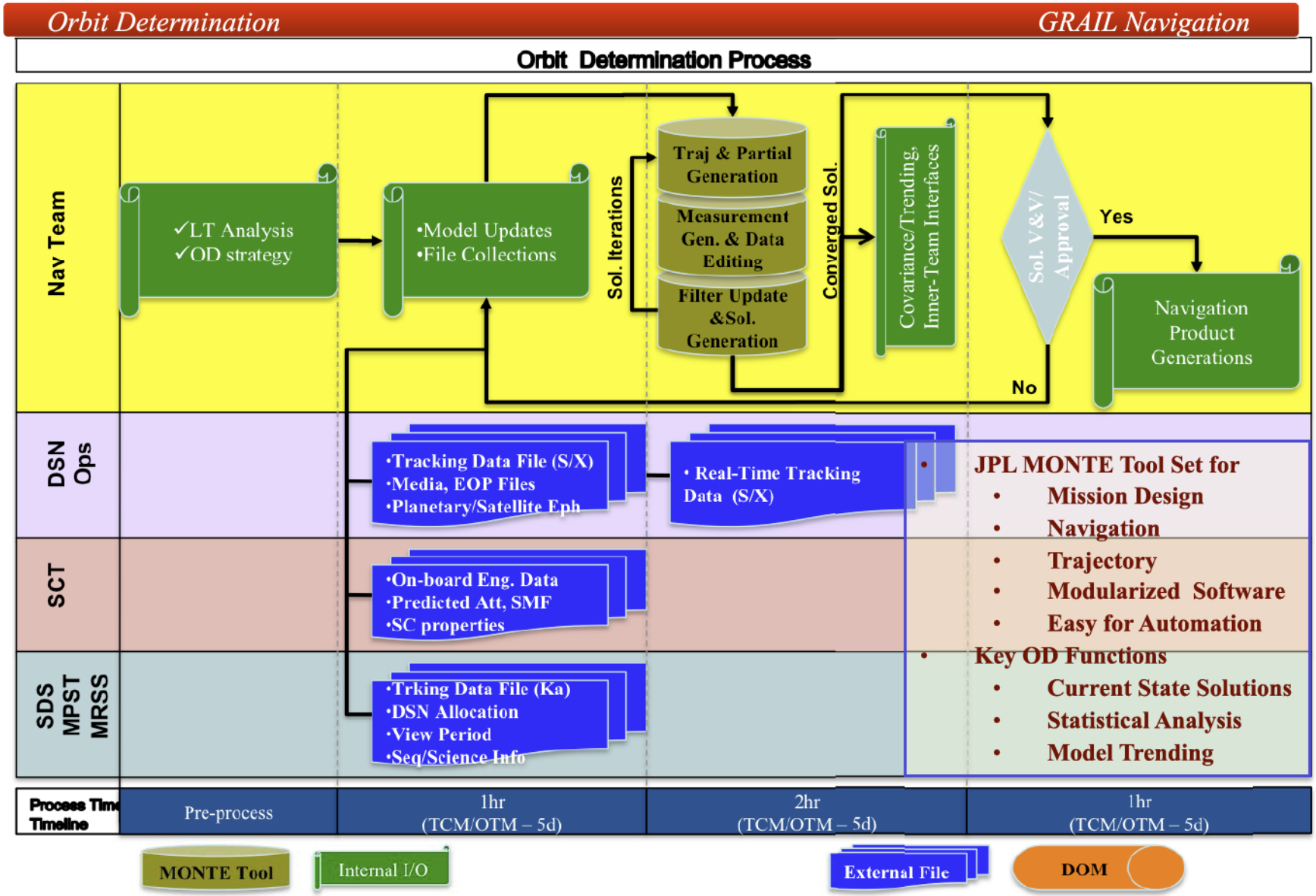
Maneuver		Epoch	Purpose
TCM-A1/B1		Launch* + 06/07 days	Statistic: Correct injection errors (Canceled)
TCM-A2/B2		Launch* + 20/25 days	Deterministic: LOI Separation
TCM-A3/B3		Launch* + 67/72 days	Deterministic: LOI Target
TCM-A4/B4		LOI – 22/18 days	Deterministic: Combined with TCM3 for LOI target optimization
TCM-A5/B5		LOI – 08 Days	Statistic: Cleanup (Canceled)
LOI	A	31 Dec 2012	Deterministic: Lunar Capture Orbit
	B	01 Jan 2012	
PRM-C1	A1-3	7-9 Jan 2012	Deterministic: Cluster-1, Period Reduction, 1 maneuver per day
	B1-3	13, 15-16 Jan 2012	
PRM-C2	A4-7	24-27 Jan 2012	Deterministic: Cluster-2, Period Reduction, 1 maneuver per day
	B4-7	31 Jan, 1-3 Feb 2012	
TSM	A1	07 Feb 2012	Deterministic: Formation to Science Orbit
	B1	14 Feb 2012	
TSM	A2	20 Feb 2012	Deterministic: Formation to Science Orbit
	B2	24 Feb 2012	
TSM-B3		29 Feb 2012	Deterministic: Science Orbit Finalization
OTM-B1		07 Mar 2012	Statistic: Cleanup (Canceled)

*Launch Time - 10 Sep 2012 13:08 UTC

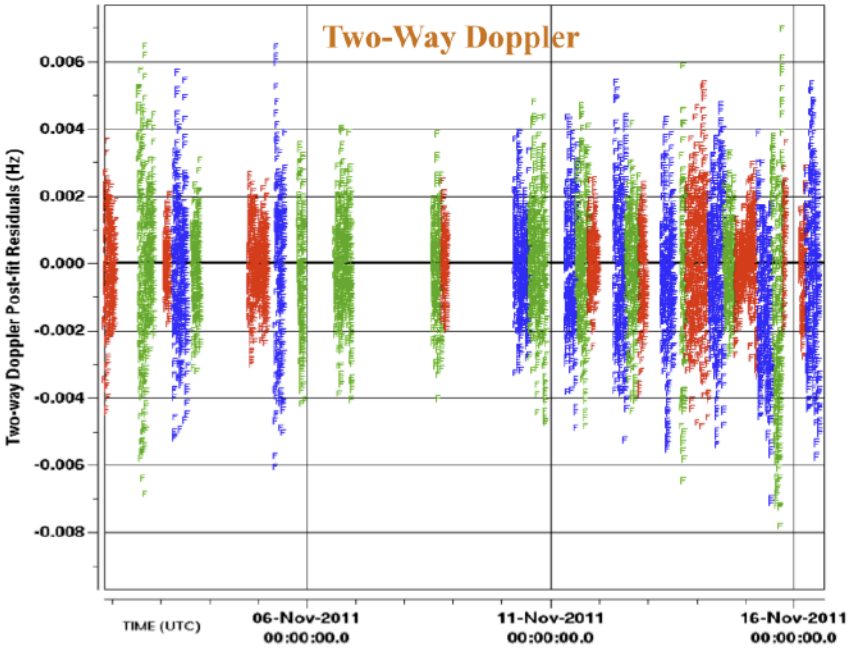


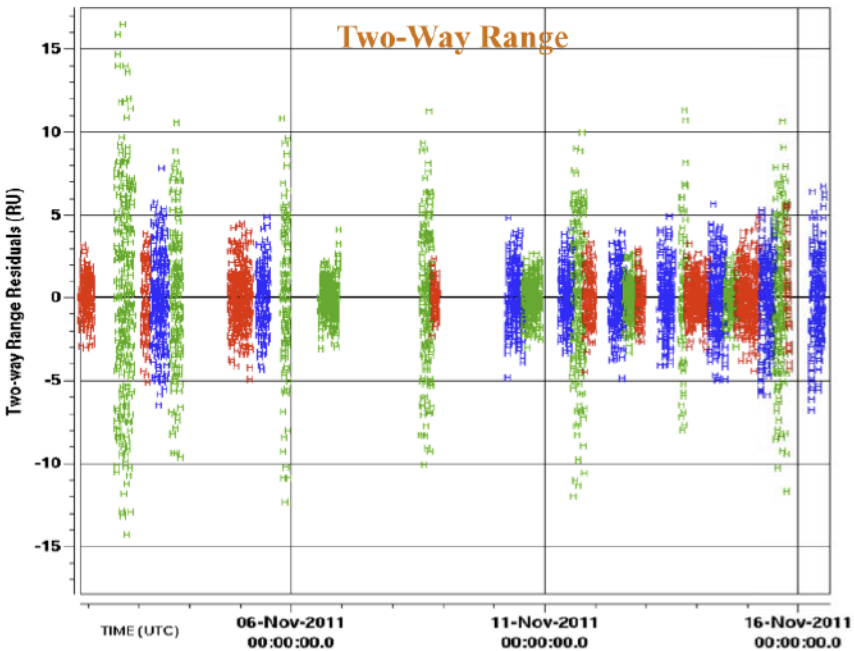
- **32 Maneuvers to Establish the Science Orbit**
  - **27 Deterministic, 5 Statistical Maneuvers**
  - **14 for GRAIL-A, 18 for GRAIL-B**
- **Thruster Calibrations Held on Early Nov'11**
  - **Results Indicated ACS System Was Reasonably Balanced**
- **DESAT Frequency Was at ~30% of the Pre-Launch Assumption in Cruise Phase**
  - **OD Analysis Showed < 1mm/s/event**

Orbit Determination Process



Tracking Data Quality

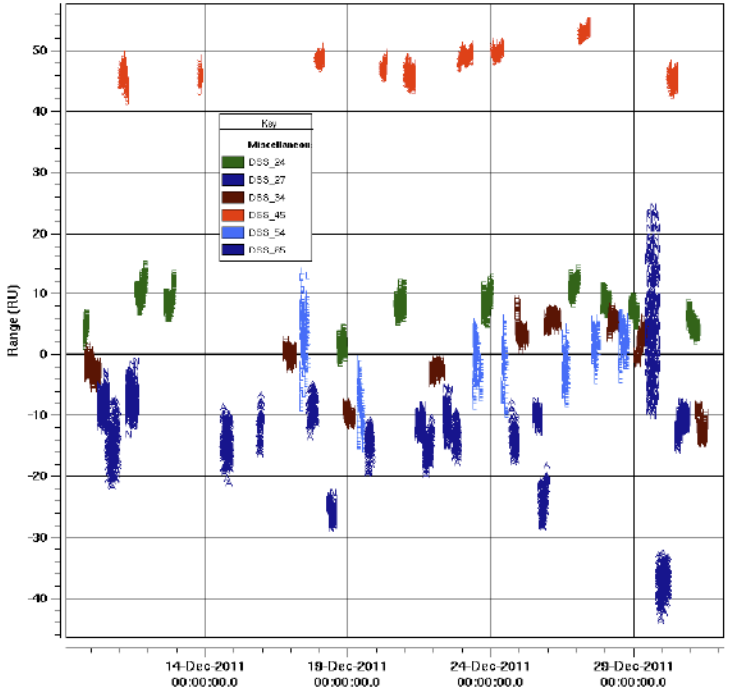


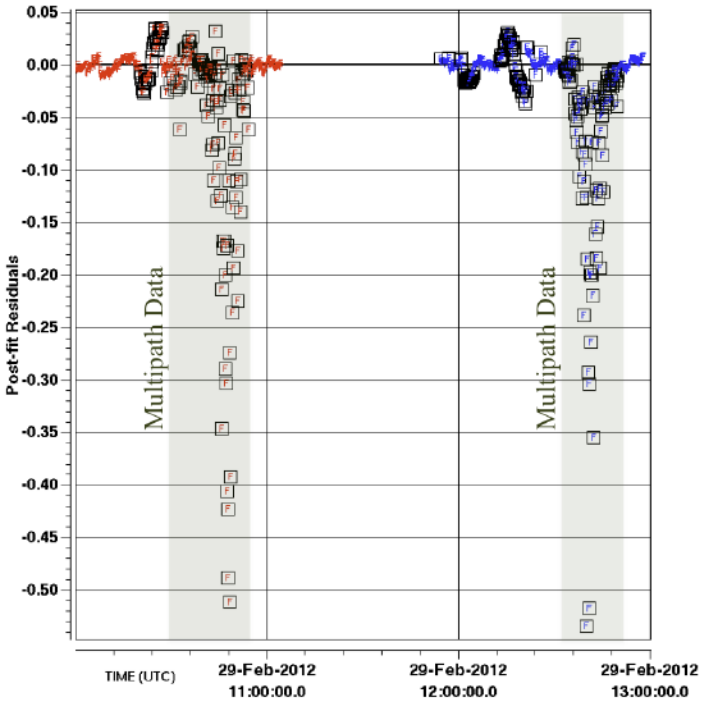


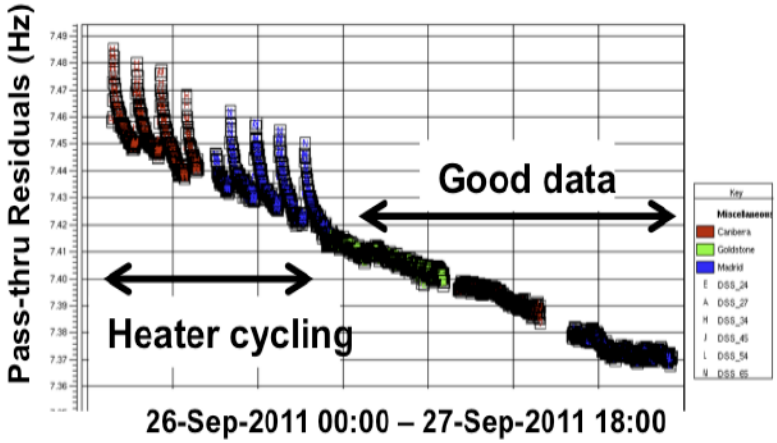
Data Type	Pre-launch Assumption (1σ)	Observed (1σ)	Remark
Two-way Doppler	1 mm/s	0.10 - 0.15 mm/s	60 second sampling 1 mm/s =~ 0.015 Hz
Two-way Range	3 m	~0.5 m	1 m =~ 7 RU

Tracking Data Problems

Orbit Determination *GRAIL Navigation*







- **Unstable X-band One-way Data**
- **Corrupted Multipath Tracking During Orbital Phases**
- **Uncharacterized Range Bias**

TLC Filter Configuration

		Baseline	No Margin			
Error Source	**Estimate Type**	**A Priori Uncertainty (1σ)**	**A Priori Uncertainty (1σ)**	**Correlation Time**	**Update Time**	**Comments**
S-Band 2-way Doppler (hz)	–	per pass	per pass			floor at 0.0015 hz
S-Band Range (RU)	–	per pass	per pass			floor at 7 RU / 4 RU
Epoch state position (km)	Estimate	100000	100000			Earth, Sun or Moon-Centered ICRF Cartesian
Epoch state velocity (km/s)	Estimate	10	10			
Solar Radiation Pressure Coefficient (% of total)	Estimate	20	5			flat plate component model
Range Bias (RU)	Estimate	50	50			Per station bias
		21	21		per pass	stochastic
Ionosphere – day / night (cm)	Estimate	20	20	white	per pass	stochastic
Troposphere – wet / dry (cm)	Estimate	2	2	white	per pass	stochastic
AMD Event ΔV (mm/s)	Estimate	Various	0.5 mm/s		per event	per axis
Solar Cal Constant Acceleration (km/s^2)	Estimate	5.00E-12	5.00E-12	white	during event time	per axis constant bias
Non-Grav Acceleration (km/s^2)	Estimate	5.0e-12 / 2.0e-12 / 2.0e-12	2.0e-12 / 2.0e-12 / 2.0e-12	white	per day	stochastic
Future Acceleration (km/s^2)	Estimate	2.00E-12	5.00E-13	white		per axis stochastic; 1.0E-11 during early TLC
Earth–Moon Ephemeris	Consider	DE421 Covariance	DE421 Covariance			~4 m lunar position error at time of Mission
Earth GM (km^3/s^2)	Consider	1.40E-03	1.40E-03			
Moon GM (km^3/s^2)	Consider	1.00E-04	1.00E-04			
Station Locations (km, deg, km)	Consider	Covariance	Covariance			
Pole X, Y (cm)	Consider	10.0 / 10.0	10.0 / 10.0			1.5e-08 radians
UT1 (cm)	Consider	10	10			0.3e-03 seconds

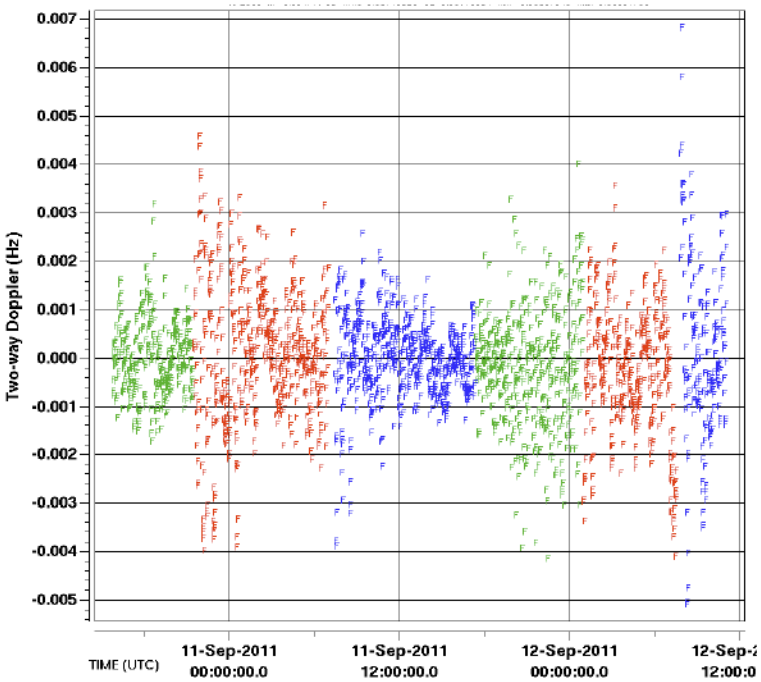
Maneuver Execution Errors (3σ)	**Estimate Type**	**Based on Model**	**ΔV magnitude**		**Pointing**		**Comments**
			Fixed	**Proportional**	**Fixed per axis**	**Proportional Total**	
TCM-1 (Canceled)	Estimate	ME Pre-Crosstrack Calibration	7 mm/s	0.25%	3 mm/s	(-4/15*|DV|+6+5/15)% for 5<DV<20 m/s	Force, Pointing (RA, Dec)
TCM-2 - TCM-3	Estimate	ME Translational-Crosstrack Calibration	7 mm/s	0.25%	1 mm/s	1.00%	Force, Pointing (RA, Dec)
TCM-4 – TCM-5* (TCM-5 Canceled)	Estimate	ME Duty Cycle	1 mm/s	1.67%	1 mm/s	0.60%	Force, Pointing (RA, Dec)

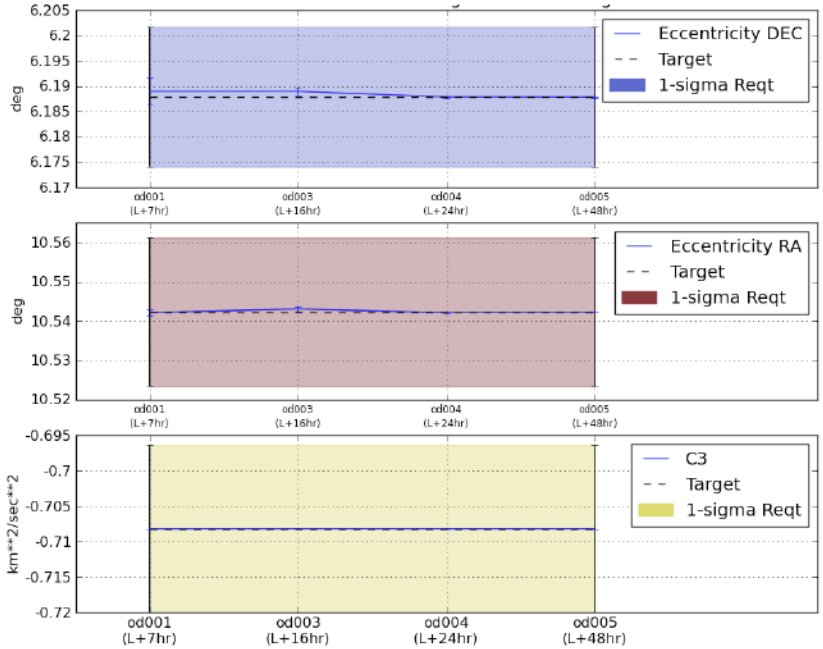
In-Orbit Filter Configuration

		Baseline					
Error Source	**Estimate Type**	**A Priori Uncertainty (1σ)**			**Correlation Time**	**Update Time**	**Comments**
S-Band 2-way Doppler (hz)	–	per pass					floor at 0.0015 hz
Epoch state position (km) **Epoch state velocity (km/s)**	Estimate Estimate	1000 1					Earth, Sun or Moon-Centered ICRF Cartesian
Solar Radiation Pressure Coefficient (% of total)	Estimate	5					flat plate component model
Ionosphere – day / night (cm)	Estimate	20			white	per pass	stochastic
Troposphere – wet / dry (cm)	Estimate	2			white	per pass	stochastic
AMD Event ΔV (mm/s)	Estimate	Various				per event	per axis
Preiapsis Absorber (mm/s)	Estimate	Various					2-5 mm/s typically
Future Acceleration (km/s^2)	Estimate	Various (Periodical)			white		stochastic; to account for gravity errors
Earth–Moon Ephemeris	Consider	DE421 Covariance					~4 m lunar position error at time of Mission
Earth GM (km^3/s^2) **Moon GM (km^3/s^2)**	Consider Consider	1.40E-03 1.00E-04					
Station Locations (km, deg, km)	Consider	Covariance					
Pole X, Y (cm) **UT1 (cm)**	Consider Consider	10.0 / 10.0 10					1.5e-08 radians 0.3e-03 seconds
Maneuver Execution Errors (3σ)	**Estimate Type**	**Based on Model**	**ΔV magnitude**		**Pointing**		**Comments**
			Fixed	**Proportional**	**Fixed per axis**	**Proportional Total**	
LOI, PRMs, TSMs	Estimate	Based ME Burn	7 mm/s	0.25%	1mm/s	0.50%	Force, Pointing (RA, Dec)

Launch Vehicle (LV) Performance

Orbit Determination *GRAIL Navigation*

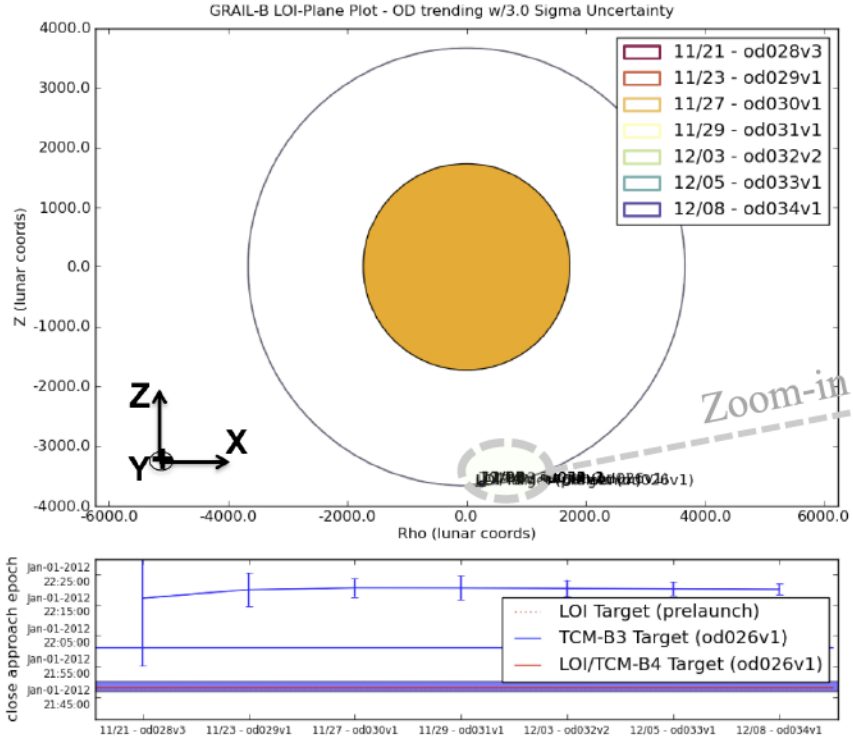


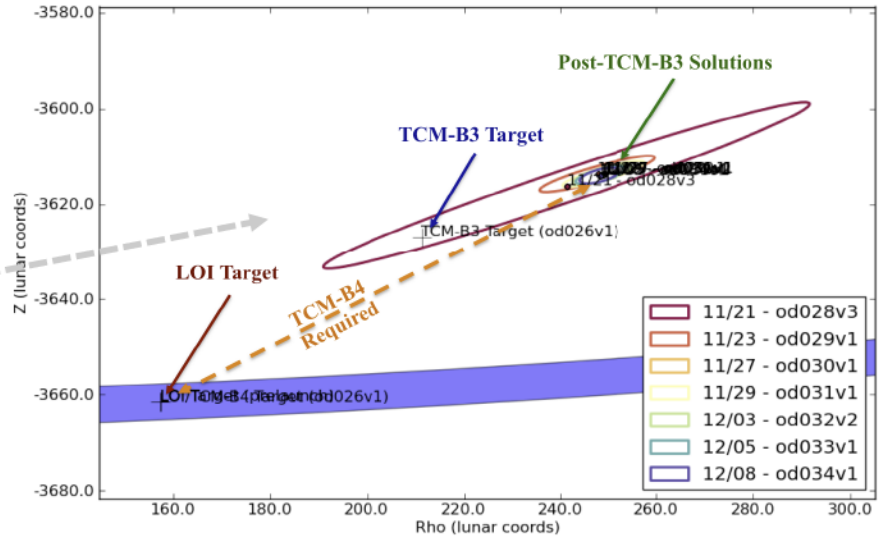


- **Evaluated Based on L+48hr Solution**
- **Remarkable LV Performance**
  - **Well within Pre-Launch Expectation**
  - **TCM1 Cancelled**

Parameter	L.V. Target	OD Reconstructed	Error (σ)
C_3 (km^2/s^2)	-0.696	-0.693	0.24
Eccentricity DEC (deg)	-6.160	-6.164	0.32
Eccentricity RA (deg)	190.543	190.548	0.28

Pseudo B-Plane Solutions





$Y_r(t)$: unit vector parallel to the Moon's velocity relative to the Earth at time t

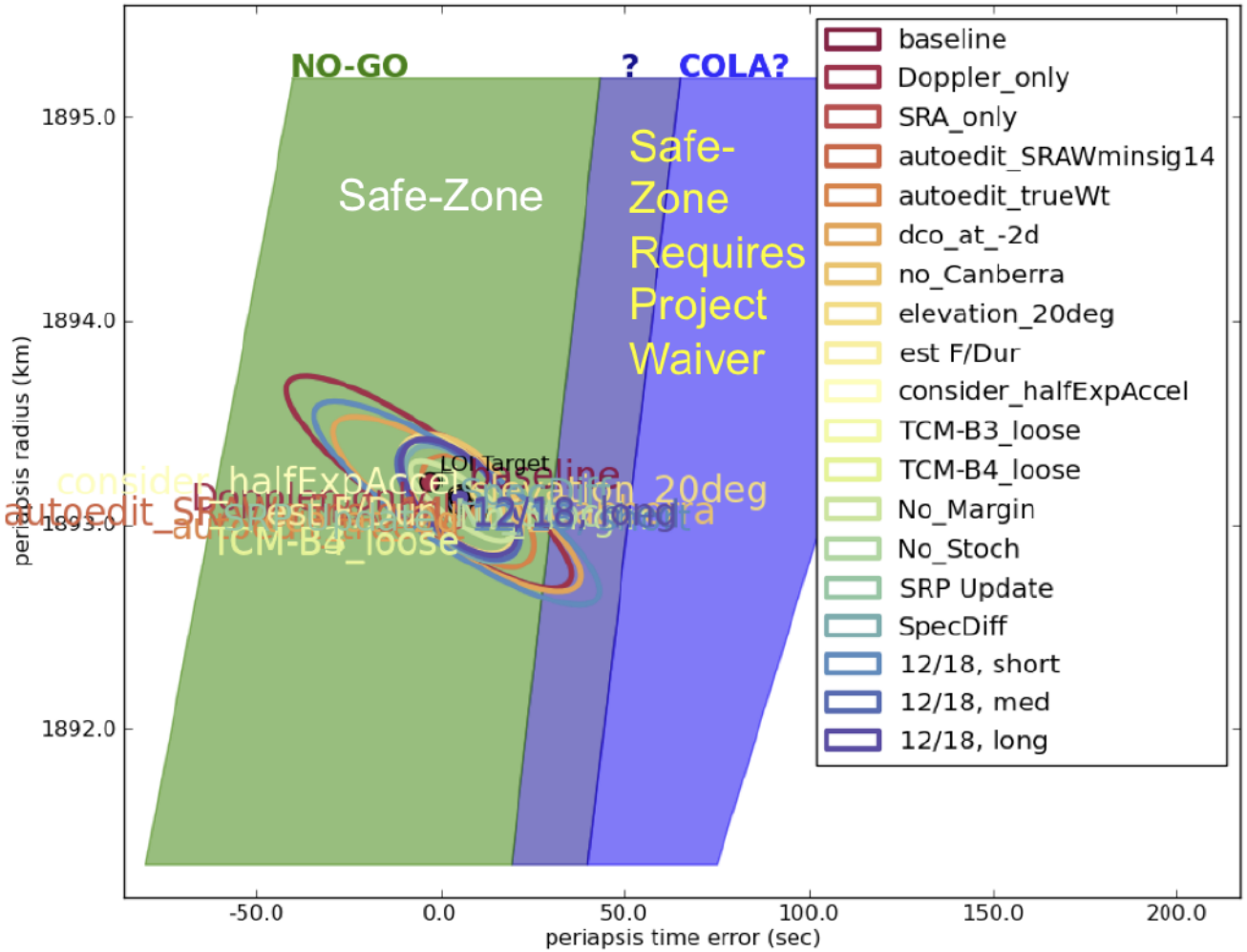
$X_r(t) = (Y_r(t) \times \varphi_r(t)) / \|Y_r(t) \times \varphi_r(t)\|$

$Z_r(t) = X_r(t) \times Y_r(t)$

The LOI-plane coordinates defined by $X_r(t_{cross})$, $Y_r(t_{cross})$, and $Z_r(t_{cross})$,

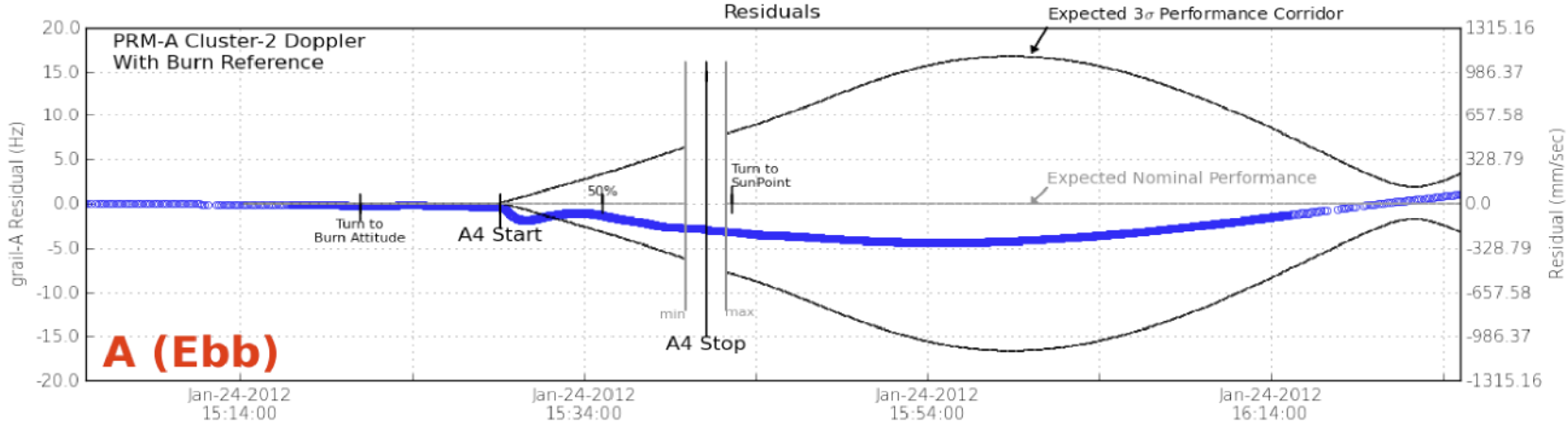
- **t_{cross} is the epoch when the nominal trajectory for GRAIL-A or GRAIL-B crosses the $X_r(t)$ -- $Z_r(t)$ plane.**

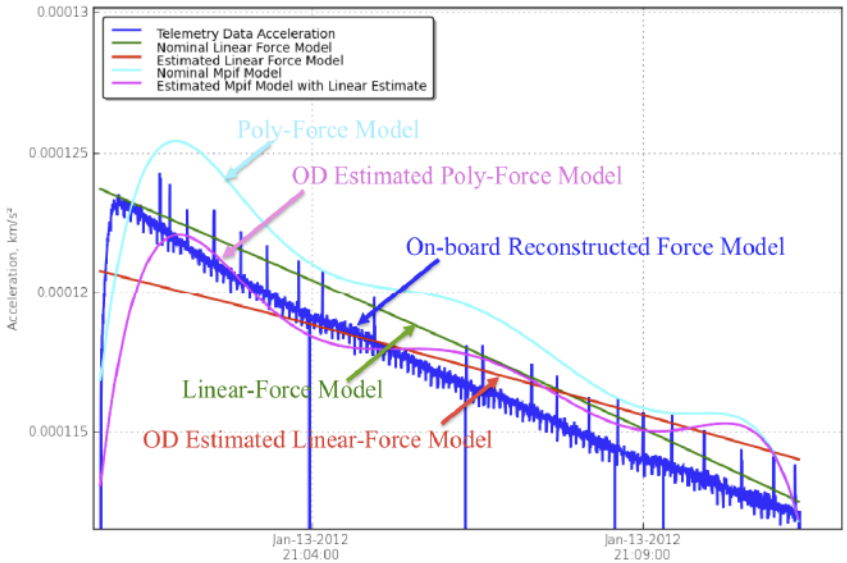
More on Solution Evaluation …

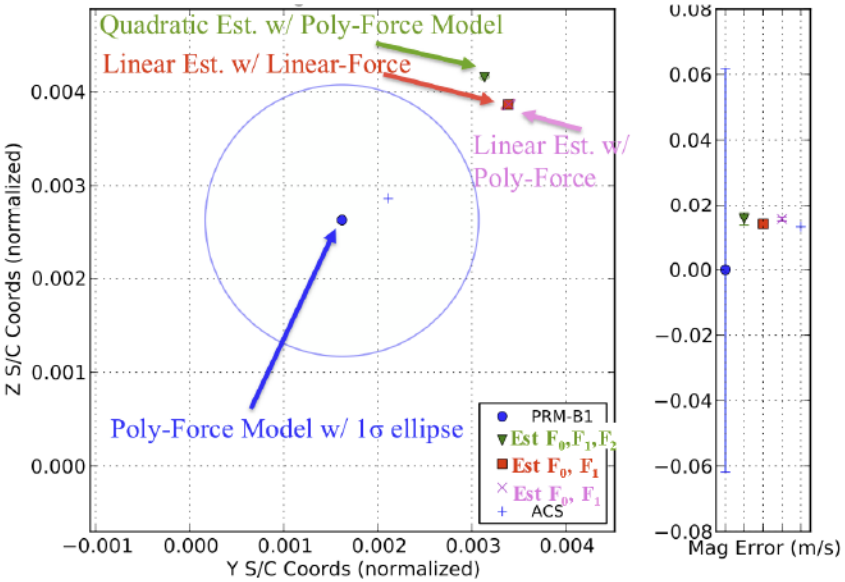


Maneuver Reconstruction

Orbit Determination *GRAIL Navigation*

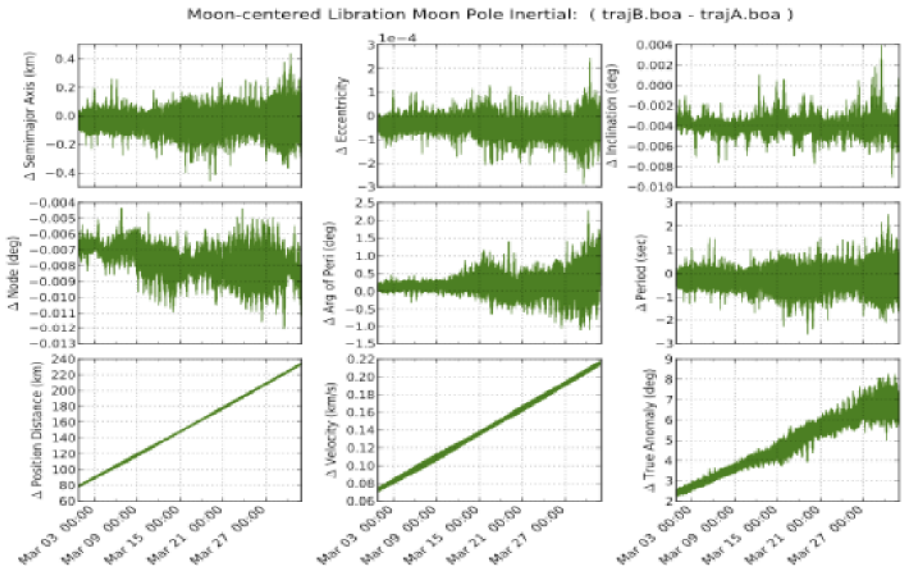


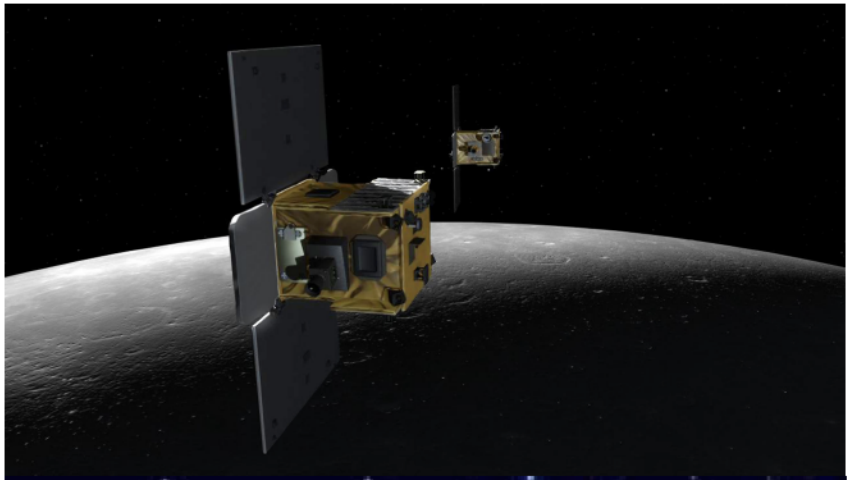


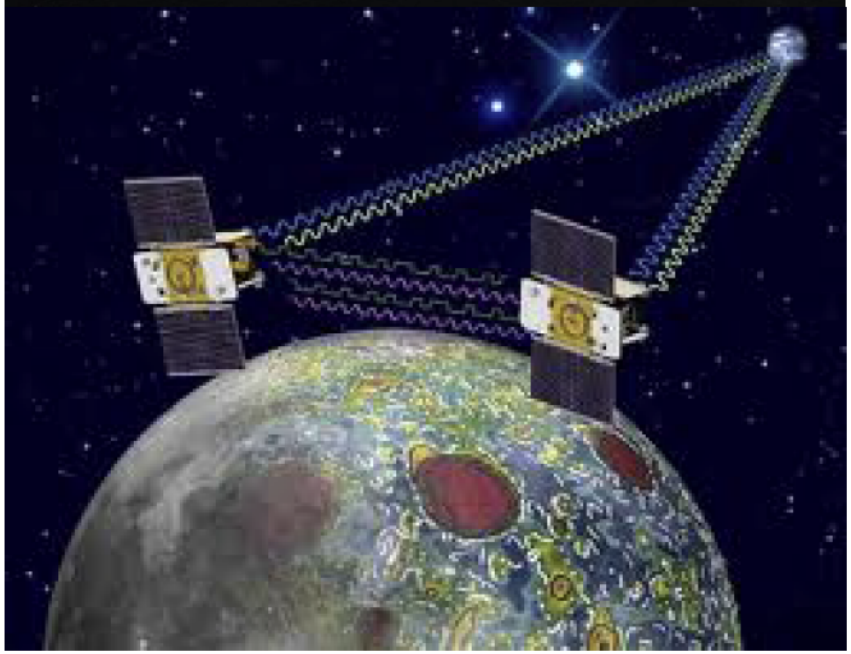


Conclusion

Orbit Determination *GRAIL Navigation*







- **27 Maneuvers in a Six-Month Journey to Establish Formation Flying**
  - **A Week Earlier than Planned**
- **Project Met Its Minimum Success Criteria at the Midpoint of the Primary Mission Phase**
- **GRAIL is on going its Extended Mission**
  - **A Total of 5 Cycles of Science Data Has Been Collected**