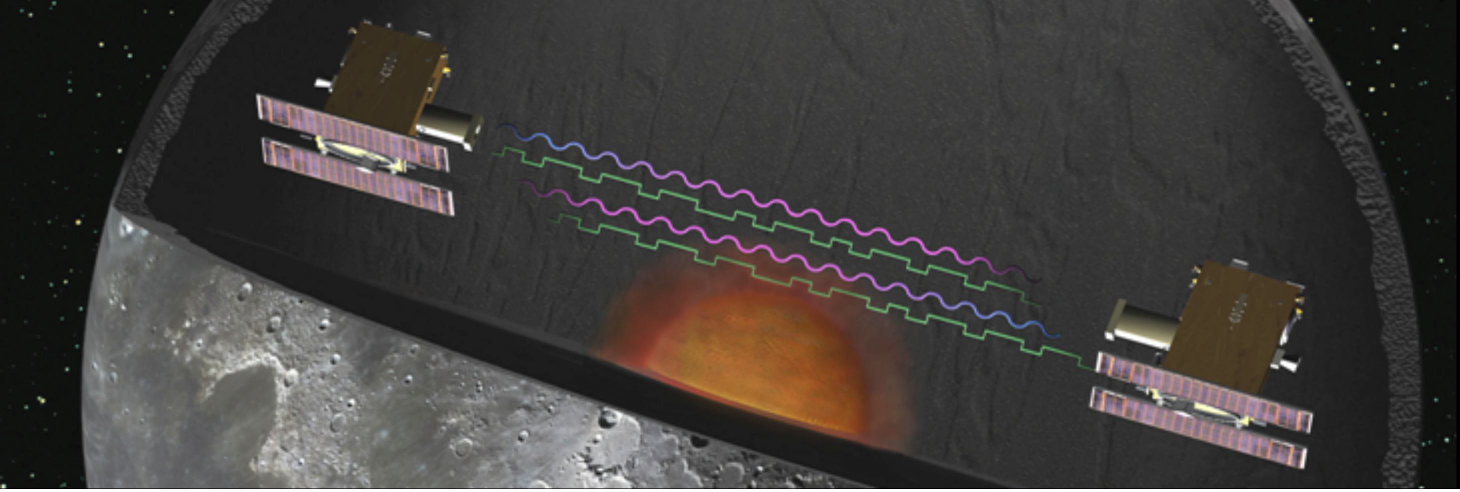

GRAIL

Gravity
Recovery
and
Interior
Laboratory

Response to KARI Questions regarding the GRAIL Mission

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November 19, 2019
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Question Summary

GRAIL
Discovery

- 35 questions received from KARI on Thursday, November 14th
  - 27 questions have been answered
  - 4 questions have been partially answered
  - 4 questions have not been answered

No.	Topic	Addressed
Q-01	Trajectory design: Launch period design	Y
Q-02	Trajectory design: LOI timing	Y
Q-03	Spacecraft performance: Main engine vs ACS thrusters	Y
Q-04	Trajectory design: Launch coast strategy	Y
Q-05	Navigation: Spacecraft outgassing	Y
Q-06	Navigation: Accelerometer usage	Y
Q-07	Navigation: Spacecraft attitude during cruise	Y
Q-08	Mission operations: LOI fault protection	N
Q-09	Maneuver design: Spacecraft attitude during LOI	Y
Q-10	Trajectory design: PRM strategy	Y
Q-11	Trajectory design: PRM strategy	Y
Q-12	Trajectory design: PRM strategy	Y
Q-13	Mission design: ΔV budget	Y
Q-14	Mission design: Contingency Playbook	Y
Q-15	Mission design: Contingency Playbook	Y
Q-16	Mission operations: LOI fault protection	N
Q-17	Trajectory design: PRM strategy	Y
Q-18	Spacecraft performance: Lunar eclipse survival	Y
Q-19	Maneuver design: Main engine vs ACS thrusters	P
Q-20	Navigation: TCM-5 Go/No-Go criteria	Y

No.	Topic	Addressed
Q-21	Spacecraft performance: LOI strategy	Y
Q-22	Mission operations: LOI strategy	Y
Q-23	Mission design: Lunar environment / multipath	Y
Q-24	Navigation: Spacecraft pointing requirements	Y
Q-25	Spacecraft performance: Star tracker misalignment	N
Q-26	Navigation: Accelerometer telemetry	Y
Q-27	Navigation: TCM-5 Go/No-Go Criteria	Y
Q-28	Navigation: Spacecraft outgassing	Y
Q-29	Navigation: Thruster calibration	Y
Q-30	Spacecraft performance: Maneuver duration	P
Q-31	Spacecraft performance: Pointing error	P
Q-32	Spacecraft performance: Maneuver implementation	N
Q-33	Navigation: TCM-5 Go/No-Go Criteria	Y
Q-34	Spacecraft performance: LOI strategy	P
Q-35	Maneuver design: Delayed TCM	Y

Legend
Y = Question has been addressed
P = Question has been partially addressed
N = Question has not be answered

Question 1

Trajectory design: Launch period design

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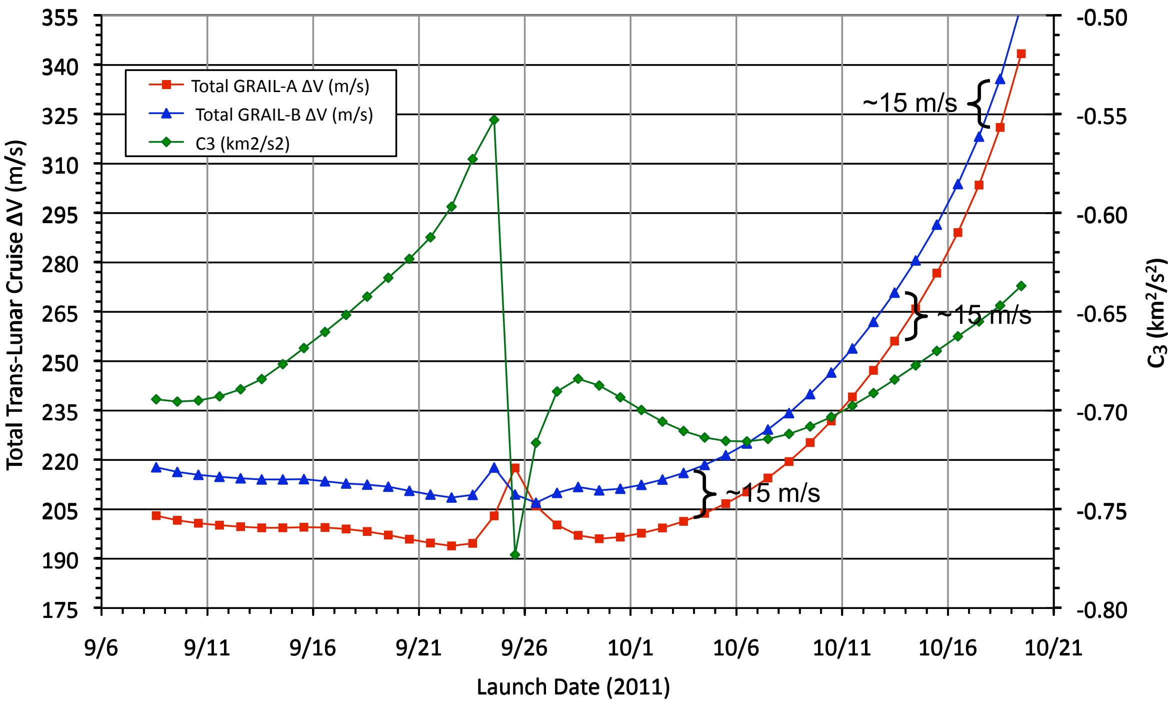
- *Launch period was 26 day and LOI was fixed date. If launch date is different among the launch period, is the shape (or BLT family type) of trajectory different or the same? Was the separation vector varies on launch date or just TCM maneuvers different with the same separation vector?*

- There is no change in the basic family of low energy trajectories, but the fixed arrival date with shorter flight time does change the "shape" of the trajectory
- Assuming that the "separation vector" refers to the launch vehicle injection target – yes, the injection targets do change from day to day throughout the launch period

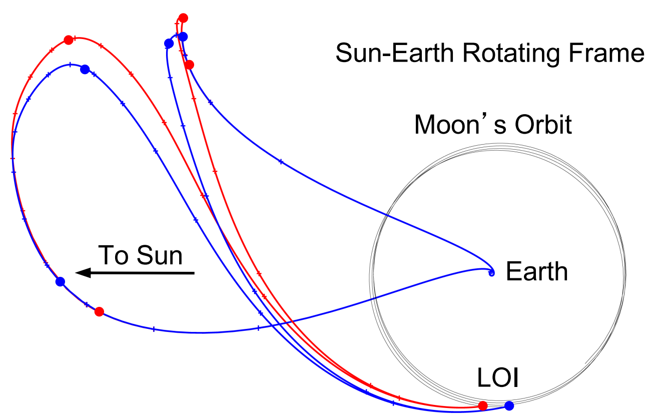
Launch Period Design

GRAIL
Discovery

- Baseline Launch Period
  - Minimize ΔV across launch period
  - Originally launch period was 26 days
- Balance GR-A and GR-B ΔVs
  - Weight the GR-A and GR-B ΔVs such that the difference in ΔVs is the same from day to day
    - Attempt to ensure that the end-of-mission ΔV margin is the same for GR-A and GR-B



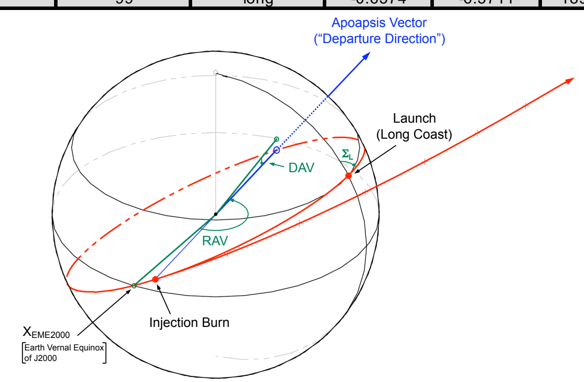
- Extended Launch Period
  - Constrained by
    - Available propellant
    - Compression of Trans-Lunar Cruise timeline (ability to "fit" all activities into a shortened TLC Phase)
  - Final launch period was 42 days long !



GRAIL Injection Targets

Launch Day	Launch Date	Launch Azimuth (deg)	Park Orbit Coast Option	C_3 (km^2/s^2)	DAV (deg) (EME2000)	RAV (deg) (EME2000)
1	08-Sep-2011	93	long	-0.6943	-6.2123	190.5757
		99	long	-0.6951	-6.2250	190.5305
2	09-Sep-2011	93	long	-0.6954	-6.1701	190.5559
		99	long	-0.6962	-6.1825	190.5152
3	10-Sep-2011	93	long	-0.6949	-6.1470	190.5776
		99	long	-0.6956	-6.1595	190.5432
4	11-Sep-2011	93	long	-0.6928	-6.1404	190.6199
		99	long	-0.6934	-6.1532	190.5918
5	12-Sep-2011	93	long	-0.6892	-6.1458	190.6689
		99	long	-0.6898	-6.1595	190.6461
6	13-Sep-2011	93	long	-0.6840	-6.1611	190.7103
		99	long	-0.6847	-6.1757	190.6926
7	14-Sep-2011	93	long	-0.6765	-6.1974	190.6724
		99	long	-0.6772	-6.2130	190.6608
8	15-Sep-2011	93	long	-0.6684	-6.2458	190.6074
		99	long	-0.6689	-6.2624	190.5986
9	16-Sep-2011	93	long	-0.6602	-6.2968	190.5576
		99	long	-0.6609	-6.3136	190.5470
10	17-Sep-2011	93	long	-0.6516	-6.3559	190.5415
		99	long	-0.6522	-6.3741	190.5326
11	18-Sep-2011	93	long	-0.6423	-6.4237	190.5662
		99	long	-0.6429	-6.4427	190.5578
12	19-Sep-2011	93	long	-0.6328	-6.4954	190.6254
		99	long	-0.6334	-6.5144	190.6159
13	20-Sep-2011	93	long	-0.6232	-6.5713	190.7140
		99	long	-0.6239	-6.5911	190.7026
14	21-Sep-2011	93	long	-0.6123	-6.6927	190.8311
		99	long	-0.6128	-6.7196	190.8106
15	22-Sep-2011	93	long	-0.5967	-6.9887	191.0129
		99	long	-0.5971	-7.0209	190.9963
16	23-Sep-2011	93	long	-0.5727	-7.2692	191.8195
		99	long	-0.5731	-7.2383	191.8450
17	24-Sep-2011	93	long	-0.5528	-4.6007	193.8251
		99	long	-0.5590	-4.2929	193.7518
18	25-Sep-2011	93	long	-0.7730	-2.5045	186.4125
		99	long	-0.7710	-2.6089	186.4590
19	26-Sep-2011	93	long	-0.7163	-4.9368	187.1531
		99	long	-0.7158	-4.9615	187.1824
20	27-Sep-2011	93	long	-0.6903	-5.4946	187.6840
		99	long	-0.6907	-5.5100	187.6879
21	28-Sep-2011	93	long	-0.6839	-5.6261	187.7262
		99	long	-0.6847	-5.6369	187.7163
22	29-Sep-2011	93	long	-0.6873	-5.6479	187.5163
		99	long	-0.6882	-5.6578	187.5097
23	30-Sep-2011	93	long	-0.6933	-5.6708	187.2789
		99	long	-0.6942	-5.6768	187.2770
24	01-Oct-2011	93	long	-0.6997	-5.6759	187.0362
		99	long	-0.7006	-5.6756	187.0381
25	02-Oct-2011	93	long	-0.7056	-5.6570	186.8034
		99	long	-0.7065	-5.6508	186.8076
26	03-Oct-2011	93	long	-0.7103	-5.6267	186.5966
		99	long	-0.7112	-5.6164	186.6023

Launch Day	Launch Date	Launch Azimuth (deg)	Park Orbit Coast Option	C_3 (km^2/s^2)	DAV (deg) (EME2000)	RAV (deg) (EME2000)
27	04-Oct-2011	93	long	-0.7137	-5.5971	186.4284
		99	long	-0.7145	-5.5838	186.4350
28	05-Oct-2011	93	long	-0.7154	-5.5756	186.3069
		99	long	-0.7162	-5.5605	186.3139
29	06-Oct-2011	93	long	-0.7156	-5.5667	186.2365
		99	long	-0.7163	-5.5508	186.2437
30	07-Oct-2011	93	long	-0.7144	-5.5730	186.2195
		99	long	-0.7151	-5.5571	186.2267
31	08-Oct-2011	93	long	-0.7118	-5.5957	186.2575
		99	long	-0.7125	-5.5801	186.2647
32	09-Oct-2011	93	long	-0.7080	-5.6354	186.3512
		99	long	-0.7087	-5.6205	186.3587
33	10-Oct-2011	93	long	-0.7032	-5.6920	186.5005
		99	long	-0.7039	-5.6778	186.5084
34	11-Oct-2011	93	long	-0.6975	-5.7645	186.7027
		99	long	-0.6982	-5.7509	186.7111
35	12-Oct-2011	93	long	-0.6912	-5.8506	186.9530
		99	long	-0.6918	-5.8376	186.9621
36	13-Oct-2011	93	long	-0.6843	-5.9474	187.2438
		99	long	-0.6849	-5.9350	187.2536
37	14-Oct-2011	93	long	-0.6771	-6.0515	187.5669
		99	long	-0.6777	-6.0396	187.5771
38	15-Oct-2011	93	long	-0.6698	-6.1597	187.9146
		99	long	-0.6704	-6.1484	187.9252
39	16-Oct-2011	93	long	-0.6624	-6.2693	188.2842
		99	long	-0.6630	-6.2581	188.2951
40	17-Oct-2011	93	long	-0.6549	-6.3786	188.6823
		99	long	-0.6555	-6.3673	188.6935
41	18-Oct-2011	93	long	-0.6468	-6.4865	189.1349
		99	long	-0.6474	-6.4740	189.1474
42	19-Oct-2011	93	long	-0.6369	-6.5873	189.7142
		99	long	-0.6374	-6.5711	189.7308



GRAIL Launch Targets
C_3 (twice the injection energy per unit mass, km^2/s^2)
DAV (declination of the injection orbit apoapsis vector, deg, EME2000)
RAV (right ascension of the injection orbit apoapsis vector, deg, EME2000)

Question 2

Trajectory design: LOI timing

GRAIL Discovery

- *TLC Phase Trajectories of GRAIL A and B are different for 1 day gap of LOI. It was done by TCM maneuvers with same initial injection trajectory. What is the maximum day gap which can be achieved by TCM with the same initial injection trajectory? Are the achievable day gap of other BLT families similar to GRAIL case?*

- Dual Spacecraft Launch on a Single Launch Vehicle
  - Two deterministic TCMs
    - TCM-2: Arrival time (LOI) separation
    - TCM-3: Manifold insertion
- ΔV cost to increase the gap to a value that was useful for mission operations (e.g. > 3 days) was considered too high (10's of m/s) for GRAIL
- The ΔV cost for other types of low energy trajectories would be similar
- For KPLO (for a single spacecraft) – there is no "gap"

Question 3

Spacecraft performance: Main engine vs ACS thrusters

GRAIL Discovery

- *The warm gas ACS were used for small maneuvers in the TSF and Science Phases. Are there any criteria to select main engine or the warm gas ACS system? It could be mission phase or del-V value. For example, if required del-V is bigger than defined value, main engine is used. If it is the del-V value, what was the value? In the Table A, TCM-A5 is 0.04 m/s which is smaller than TSF burn del-V. In that case, which thruster was used?*

- The selection of which system to use (i.e. main engine or ACS thrusters) is driven by the expected maneuver execution errors – which are a function of the spacecraft design
- The selection of which system to use is often dictated by the size of the ΔV
- TCM-5 for both GRAIL-A and GRAIL-B was cancelled
  - The option existed to perform the maneuver using either the main engine (in a duty-cycled mode) or the ACS thrusters

Question 4

Trajectory design: Launch coast strategy

GRAIL
Discovery

- *Each day in launch period, there are two launch opportunities with azimuth 93 and 99 degrees which called short coast or long coast. For GRAIL, long coast was selected for smaller TLC DV even it has longer time in LV. Is the long coast generally has smaller TLC DV than short coast? Or was it only for GRAIL case or Delta 2 launch vehicle only?*

- The ΔV cost to get to the Moon using a low energy trajectory is dependent on the parking orbit coast strategy, but it is not a given that the long coast will result in a smaller ΔV
- Which coast strategy results in the smaller ΔV is dependent on the trajectory geometry – including things like approaching the Moon over the north pole or the south pole
- All cases need to be analyzed to determine the lowest ΔV cost

Question 5

Navigation: Spacecraft outgassing

- *Does out-gassing impact on trajectory? Does it induce some DV?*

- Yes, spacecraft outgassing has an impact on the trajectory
- Outgassing is very spacecraft dependent
- For GRAIL, post-launch orbit determination analysis determined that the outgassing accelerations decayed to an insignificant level in about two weeks
- While the accumulated ΔVs imparted from the outgassing activities could reach a few mm/s per event, overall they were not significant enough to impact the navigation performance during translunar cruise or orbital mission phases

Question 6

Navigation: Accelerometer usage

- *Navigation during the TLC Phase is performed relying only on two-way S-band Doppler and range data. What was the role of accelerometer during TLC? In the page 8, there is a sentence "the IMU will be used for DV measurement and cutoff during all main engine burns." Was the measured DV of TCMs not used for orbit determination or prediction? If not, what was the reason? For example, was resolution of accelerometer not enough for OD? In KPLO, we don't have accelerometer now. We'd like to know the IMU is necessary for TLC phase. Burn cutoff will be done only by absolute time command.*

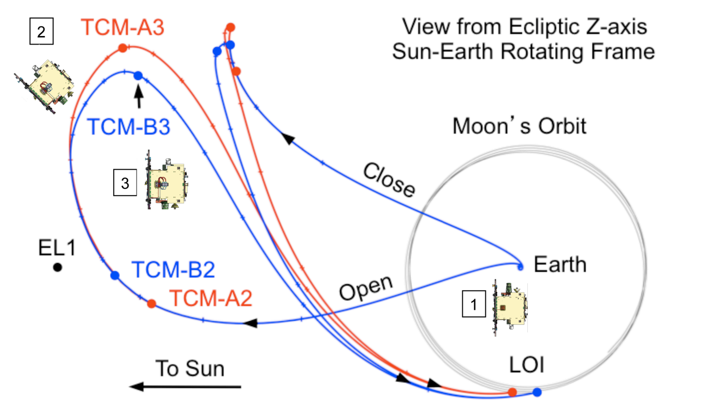
- The accelerometer was used in larger maneuvers to determine when the desired ΔV had been achieved (i.e. "ΔV cutoff"). A timer was used as a backup.
- The accelerometer data (if available) was use to construct a force profile in the orbit determination (OD) process (to estimate the maneuver parameters). The maneuver performance was then determined by the OD process.
- The estimated maneuver parameters were used to improve / fine-tune the future maneuvers
- The accelerometer data can be used in the OD process, but it does not provide full information for the maneuver reconstruction

Question 7

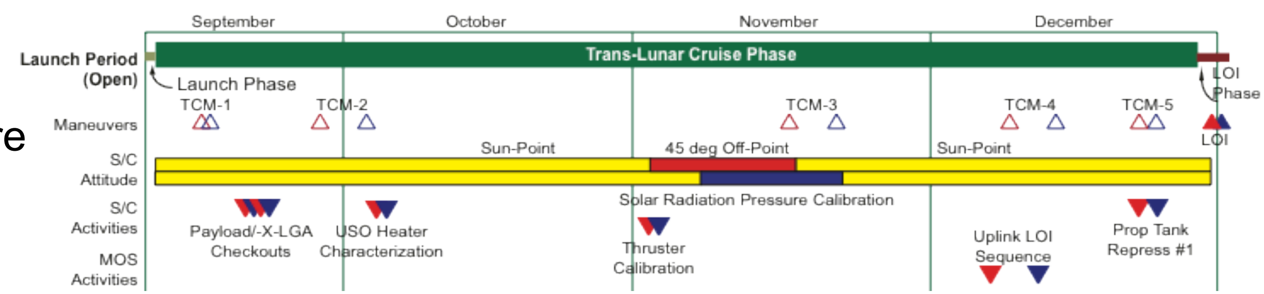
Navigation: Spacecraft attitude during cruise

GRAIL
Discovery

- *There are some advantage of off point +45 and -45 degrees during TLC (facilitate outgassing, determine translation dv during reaction wheel desaturation, estimate solar radiation pressure). Is this method conventional for spacecraft following BLT or specially designed for GRAIL mission? Are there any paper or technical memo describing this operation, method to determine translation dv, or estimation solar radiation pressure?*



- Exposing spacecraft surfaces to the Sun during cruise – that might not otherwise be exposed or would only be exposed at a later, more important time in the mission from a science or navigation perspective – is not an uncommon practice
- The practice is not unique to the GRAIL mission or a low energy trajectory
- Information on how to model or estimate things like solar radiation pressure in the orbit determination process can be found in academic text books



Question 8

Mission operations: LOI fault protection

GRAIL
Discovery

- *Before LOI, fault protection will be reconfigured. Which might disable non-essential fault protection to prevent safe mode transition. What was fault protection still enabled even at the LOI. In KPLO we have plan to enable only attitude error detection during burn. I'd like to know GRAIL's fault management philosophy.*

- I don't have detailed information on the fault protection strategies used on GRAIL

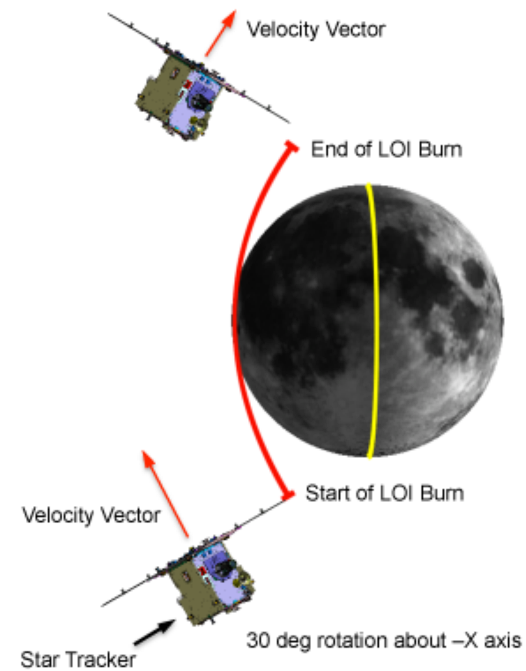
Question 9

Maneuver design: Spacecraft attitude during LOI

GRAIL
Discovery

- *Attitude during LOI maneuver was constant pitch rate thruster vector steering to reduce gravity losses. Was it simple constant pitch rotation or some control such as aligning thrust vector to anti-velocity direction or fixed attitude in LVLH frame etc? If it is simple rotation, when the rotation starts and ends? and how to decide constant pitch rate? In KPLO, we maintain inertially fixed attitude during LOI. We may have to compare the attitude strategies.*

- The attitude of each spacecraft was designed to "pitch over" at a pre-defined (constant) rate such that the main engine thrust vector was roughly aligned with the velocity vector
- A constant pitch rate strategy is not "optimal", but it is very close and it's much easier to implement than an optimal steering profile
- The determination of when to start and stop the burn and what the initial attitude should be is part of the maneuver optimization process and is a function of the spacecraft design/performance



Question 10

Trajectory design: PRM strategy

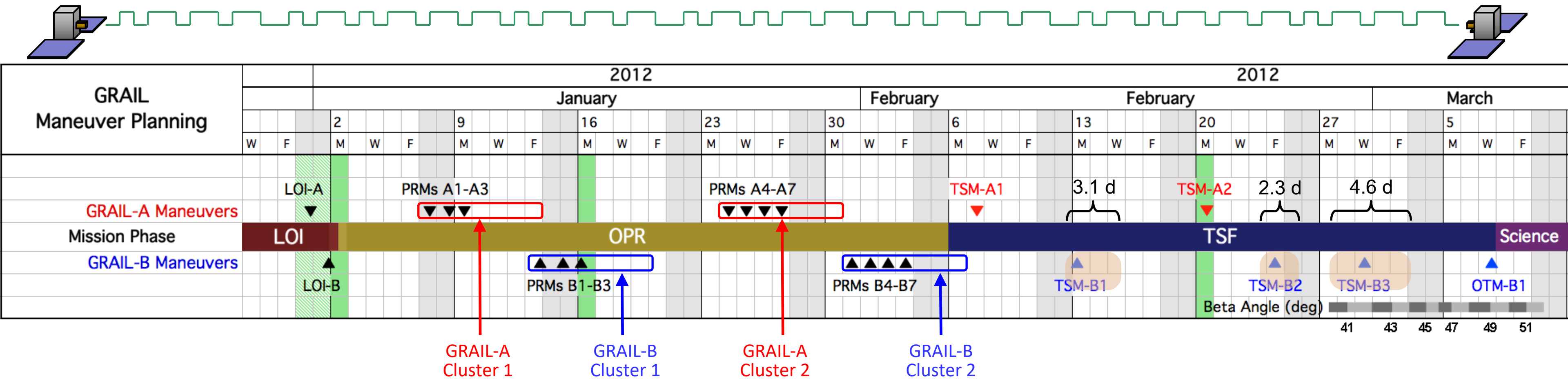
GRAIL Discovery

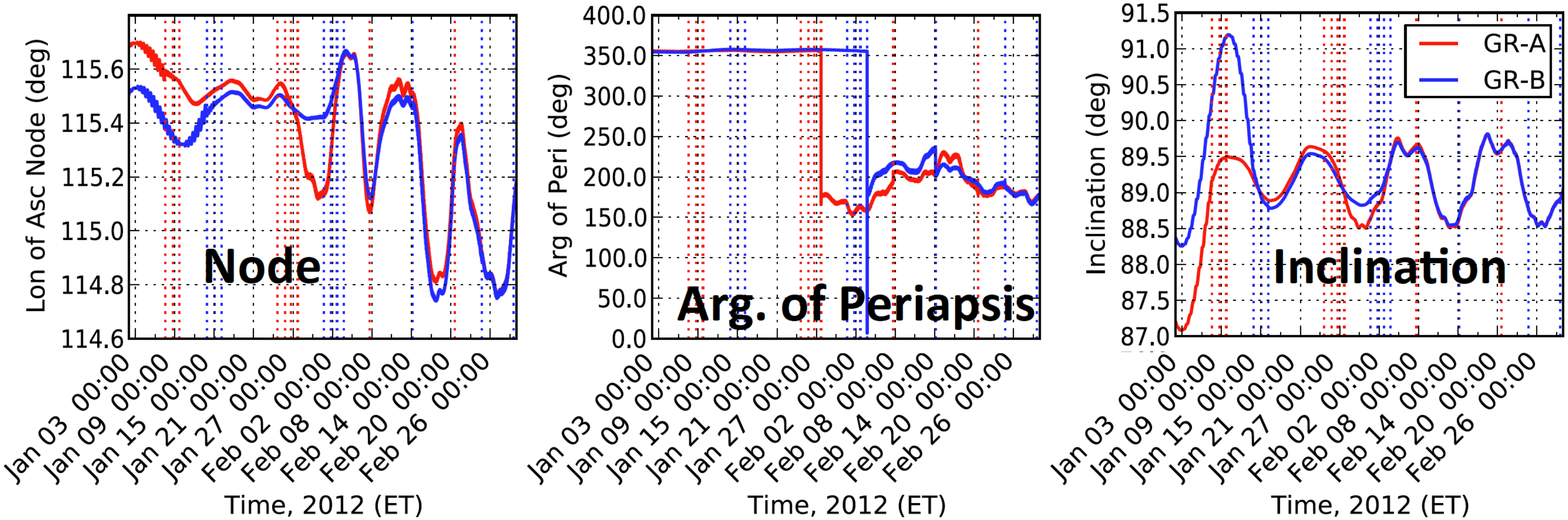
- *GRAIL achieved low lunar orbit by LOI and PRM for five weeks. Many other lunar orbiter did it by only several LOI maneuvers in few days. Is PRM required for mission with BLT trajectory? If not, is there any reason you selected PRM for five weeks rather than LOI for few days?*

- An extended Orbit Period Reduction (OPR) Phase is not required nor associated with the low energy trajectory used to get to the Moon
- The number of maneuvers was designed to reduce the gravity losses of the Period Reduction Maneuvers (PRMs)
- The timing of the maneuvers were alternated on GRAIL-A and GRAIL-B in order to ensure that the orbits "evolved" in a similar manner – since they eventually had get into the same orbit plane (inclination and node)
- The timing was also influenced by the orbit beta angle (i.e. when science data collection could start) and by a desire to minimize the ΔV required to manage the evolution of the orbit eccentricity (i.e. to avoid unnecessary eccentricity correction maneuvers)

OPR Phase – PRM Timing and Orbit Evolution

GRAIL Discovery

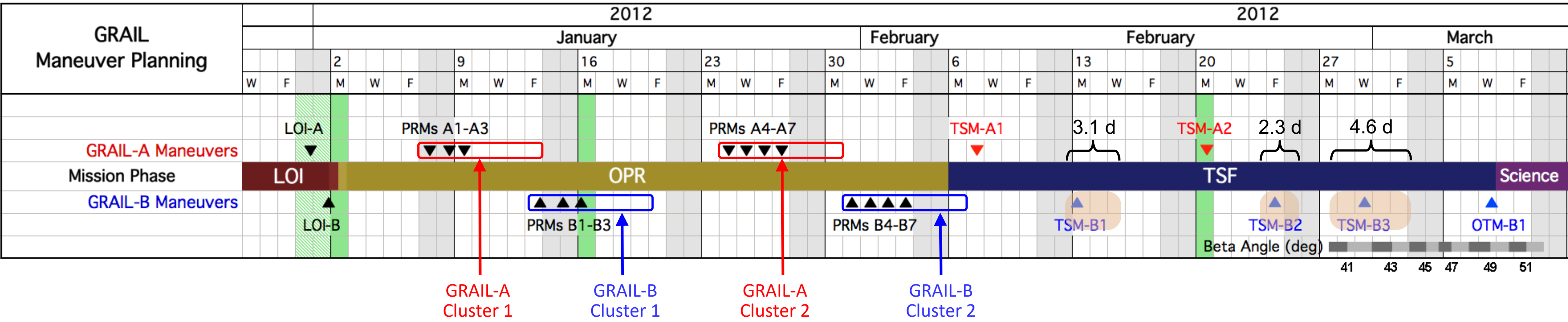




Question 11
Trajectory design: PRM strategy

GRAIL
Discovery

- *Was there a rule or principle to decide PRM duration? If we divide PRM to smaller duration, can we reduce gravity loss more? Are there any side effect?*

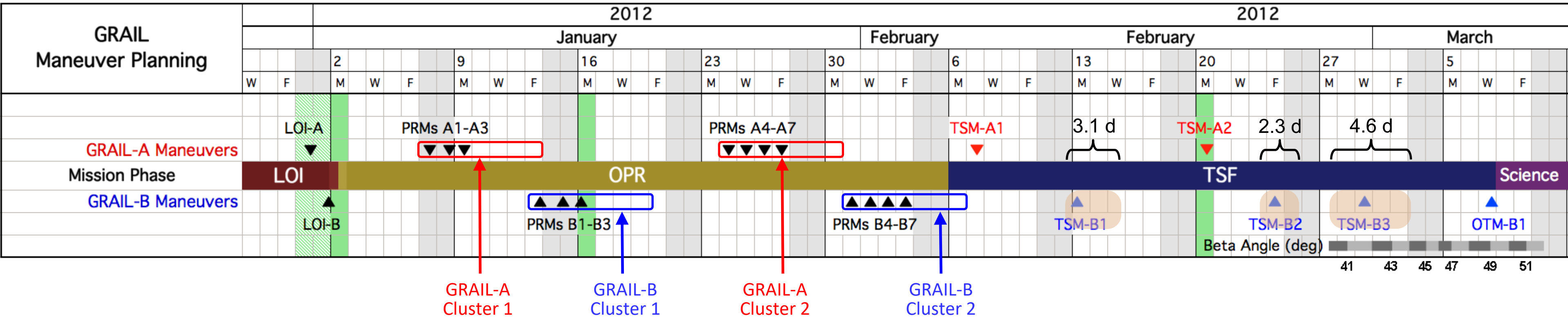


- Increasing the number of PRMs will reduce the gravity losses, but at a cost of increasing mission operations complexity

Question 12
Trajectory design: PRM strategy

GRAIL
Discovery

- *Period Reduction Maneuvers (PRMs) within a cluster is performed in the same inertial direction and with the same del-V. Is the attitude during PRMs inertially fixed? Was it different from constant pitching rate rotation of LOI maneuver? Was the pitching rotation for gravity loss reduction in LOI maneuver not required for PRMs?*



- The spacecraft attitude during the PRMs is held inertially fixed throughout the burn
- A single maneuver design (ΔV and attitude) was repeatedly performed within a cluster
- Increasing the number of burns reduced the ΔV of any single burn – and thus reduced the gravity losses – making it unnecessary to perform a pitch-over maneuver during the PRMs to reduce gravity losses further

Question 13

Mission design: ΔV budget

- *In Table A (GRAIL Mission del-V Budget), contingencies as unallocated margin was described. What is the difference between this contingencies (as unallocated margin) and mission contingencies of the upper row (considered for margin item)?*

- The items listed "here" represent things that a robust mission ΔV budget should accommodate (i.e. the "Margin" should cover these things)
- The items listed "here" identified some numbers for "known" items (either by analysis or "allocation") not yet captured in the ΔV budget
- The remaining ΔV is identified as "Unallocated Margin" (or Unencumbered Margin) – i.e. for "unknown unknowns".

Msn Phs	GRAIL-A Maneuver	GRAIL-A ΔV (m/s)	GRAIL-B Maneuver	GRAIL-B ΔV (m/s)	Maneuver Description
TLC	TCM-A1	21.4	TCM-B1	22.7	Correct launch vehicle injection errors
TLC	TCM-A2	12.4	TCM-B2	26.8	LOI separation (primarily deterministic)
TLC	TCM-A3	11.1	TCM-B3	6.3	Manifold insertion (primarily deterministic)
TLC	TCM-A4	0.38	TCM-B4	0.82	Correct TCM-3 errors
TLC	TCM-A5	0.06	TCM-B5	0.04	LOI targeting
TLC					TCM ΔVs scaled such that the sum = ΔV(99)
TLC	Total ΔV(99) = 45.4		Total ΔV(99) = 56.6		99% ΔV (deterministic + statisical)
LOI	LOI-A	191.7	LOI-B	193.7	Lunar orbit insertion (period 11.5 hours)
OPR	PRMs A1-A3	3 x 78.7	PRMs B1-B3	3 x 76.1	Period reduction (post ΔV period ~ 3.7 hours)
OPR	PRMs A4-A7	4 x 71.2	PRMs B4-B7	4 x 70.0	Period reduction (post ΔV period ~ 1.9 hours)
LOI OPR		1.3		1.3	Statistical ΔV associated with LOI/OPR ΔV(99)
TSF	TSM-A1	11.7	TSM-B1	24.3	Orbit targeting (a, e, ω) + minor period reduction
TSF	TSM-A2	11.6	TSM-B2	3.4	Establish orbit formation (GR-B leads GR-A)
TSF			TSM-B3	0.4	Establish separation distance/rate for start of Science
TSF			TSM-B4		Refine separation drift rate (with ACS)
SCI			OTM-B1	0.02	Change separation drift rate (with ACS)
SCI			OTM-B2	0.03	Change separation drift rate (with ACS)
DCM					No Decommissioning ΔV requirements
Sub-Total ΔV		782.4		787.8	**Translational ΔV (without margin)**
	Margin	71.4	Margin	65.7	ΔV margin intended to cover: • Statistical ΔV in TSF and Science Phases • Design and modeling errors for TSMs • Variation across launch period • Mission contingencies
Total ΔV		853.8		853.5	**Translational ΔV Capability (with margin)**
					ΔV Liens and Encumbrances
TLC		12.0		3.0	Worst case launch dates: GR-A 9/25, GR-B 9/24
TSF		10.0		10.0	Estimate of ΔV variation during TSF Phase
All		25.0		25.0	Contingencies (ΔV for delayed/recovery maneuvers)
Total		24.4		27.7	**Unallocated Margin**

Question 14

Mission design: Contingency Playbook

GRAIL

Discovery

- *There is "Contingency Playbook" to describe maneuver strategies to recover from missed maneuvers. Is there any public material or paper describing it?*

- No, there is no public material available associated with the Contingency Playbook

Question 15

Mission design: Contingency Playbook

GRAIL
Discovery

- *What kind of situation is included in 450 cases for various missed maneuver scenarios?*

- The stated purpose of the Contingency Playbook was the following:
  - The Contingency Playbook describes the Project response to a delayed or missed maneuver during the GRAIL OPR (Orbit Period Reduction) and TSF (Transition to Science Formation) mission phases. The objective of these recovery strategies is to minimize potential delays to the start of science data collection, and where possible, to define a path that will provide an expedient return to the baseline Mission Plan timeline.
- None of that is relevant to the KPLO mission

Question 16
Mission operations: LOI fault protection

GRAIL
Discovery

- *If contingency such as partial execution of LOI maneuver, do we have to prepare recovery burn at that moment? Or every possible contingency plan has to be prepared before? How about the automated tools for GRAIL?*

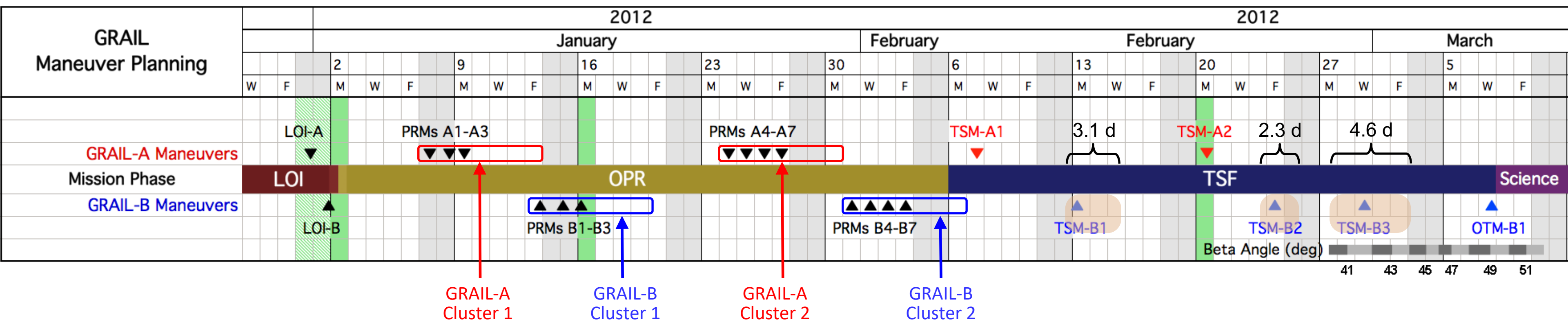
- The response to an anomaly that occurs during a mission critical event like LOI is completely determined by the risk philosophy of the project and the capabilities designed into the spacecraft and the mission operations system

Question 17

Trajectory design: PRM strategy

GRAIL
Discovery

- *In lesson's learned 3), two maneuvers per day during the second PRM were released to one maneuver per day as orbiter propellant margins increased. Does this mean that two burns a day is better than one burns a day for propellant saving? That means GRAIL could have long OPR and TSF phase for operation relaxation because propellant had margin.*



- At one point in the development of the GRAIL mission, two maneuvers were planned per day in Cluster 2 (i.e. 8 maneuvers vs 4 maneuvers)
- As the propellant margin improved, the decision was made to simplify mission operations by changing to one maneuver per day in Cluster 2 and accept the increased ΔV in gravity losses
- This did not change the overall mission timeline

Question 18

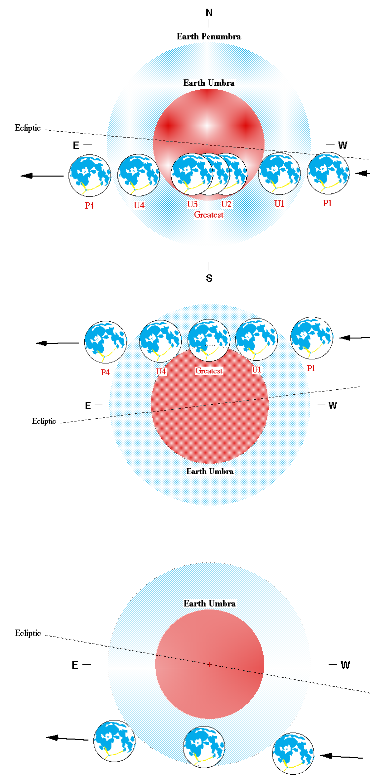
Spacecraft performance: Lunar eclipse survival

GRAIL
Discovery

- *Survival of the lunar eclipses was not a spacecraft design requirement. However, GRAIL survived during the lunar eclipse and extended mission. What was the reason to satisfy lunar eclipse survival? Was power consumption over-estimated? Or, was any special spacecraft operation to survive during lunar eclipse designed before mission extension?*

- The GRAIL spacecraft did not have the energy storage capacity to survive the total lunar eclipse in December 2011
- Survival through the partial lunar eclipse in June 2012 was accomplished through careful analysis of the in-flight performance of the spacecraft
- Orbit phasing to maximize the amount of sunlight reaching the spacecraft was analyzed, but was ultimately determined to be unnecessary to survive the partial lunar eclipse
- There was no concern regarding the penumbral lunar eclipse in November 2012

Lunar Eclipses



10-Dec-2011

4-Jun-2012

28-Nov-2012

Question 19

Maneuver design: Main engine vs ACS thrusters

- *TCM-4s were performed in 15% pulse-mode, as they were small maneuvers, 0.25 m/s. The "duty-cycle" maneuvers were not part of the pre-launch mission plan. Does the spacecraft design include duty-cycle maneuver? How it works? Was the nominal maneuver function not available for the small maneuver? I'd like to check whether KPLO burn function can do the similar small maneuvers.*

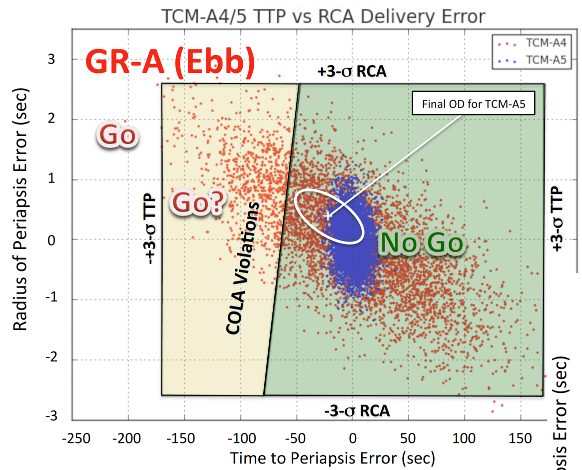
- It was determined that a duty-cycled main engine maneuver provided better accuracy for small ΔVs

Question 20

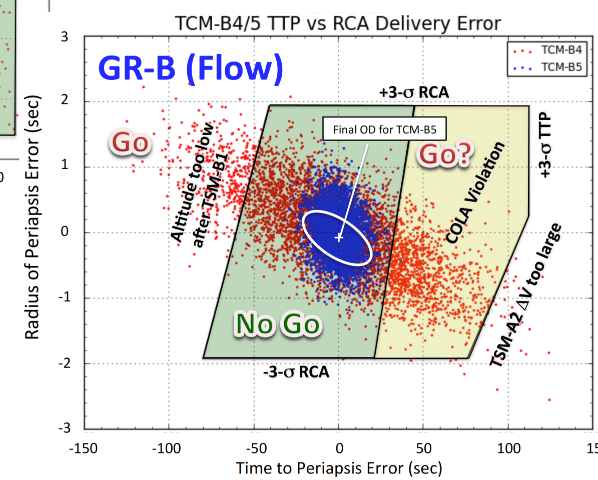
Navigation: TCM-5 Go/No-Go criteria

- *Is the Go/No-Go Criteria for TCM-5 generally applicable method for BLT or specially designed for GRAIL mission which requires formation flight?*

- TCM-5 Go/No-Go criteria were developed specifically for the GRAIL mission – they are not generally applicable to low energy transfers
- TCM-5 Go/No-Go criteria should be developed to satisfy the mission requirements



TCM-A5 canceled
TCM-B5 canceled



Question 21

Spacecraft performance: LOI strategy

- *What is main cutoff method for LOI? Was it accelerometer value or time?*

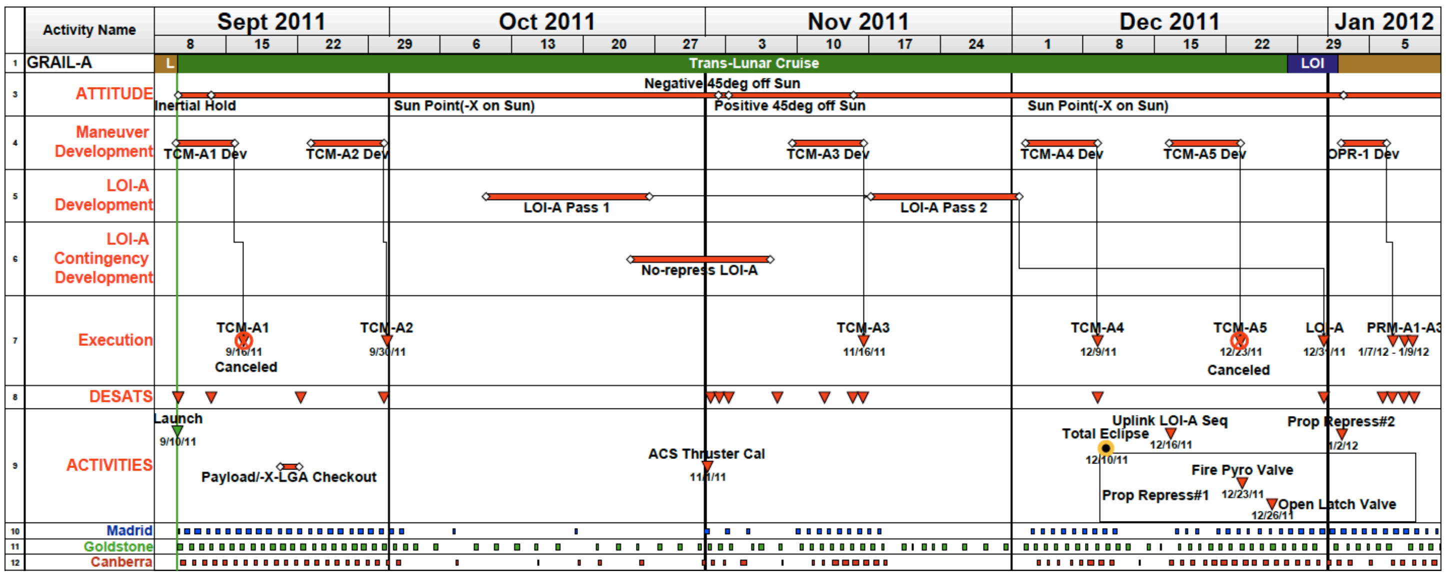
- The accelerometer was the primary method used to determine when the desired LOI ΔV had been achieved (i.e. "ΔV cutoff"). A timer was used as a backup.

Question 22

Mission operations: LOI strategy

GRAIL
Discovery

- *LOI was on ~~December 26 and 27~~ December 31 and January 1. The sequences had been uploaded on December 16. It is 10 days before the LOI. It seems quite long day. Was there any possibility of command change after final orbit determination? Was the burn execution time modified before LOI?*



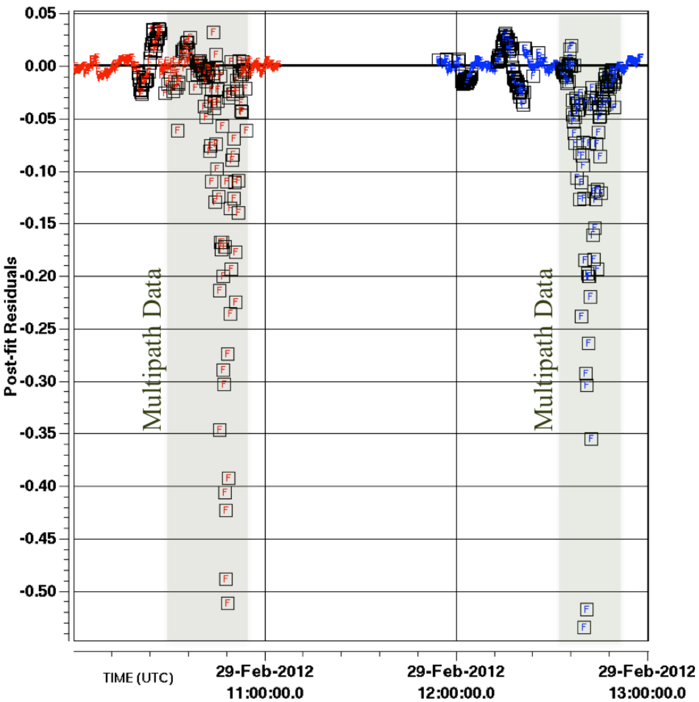
- The final TCMs were designed to achieve conditions that were favorable to the existing LOI design (i.e. to ensure that the existing LOI design was correct)
- GRAIL had the ability to update the LOI magnitude and burn start time prior to LOI, if necessary

Question 23

Mission design: Lunar environment / multipath

- *Multi-path effect occurred when Earth was near 90 degrees to the LGA boresight. Is it common for lunar orbiters, or does specific mechanical characteristic of GRAIL such as LGA orientation and spacecraft attitude caused the problem? If is is common, how can we avoid the problem by operation?*

- Doppler data were occasionally corrupted when signals transmitted from the spacecraft bounced off of the lunar surface before reaching the ground receiver
- This multipath effect is not unique to GRAIL – it can occur with any lunar orbiter given a specific combination of low altitude, spacecraft attitude, and orbit geometry



Question 24

Navigation: Spacecraft pointing requirements

- *The ephemeris pointing error requirement was 0.073 deg (1sigma). What does "ephemeris pointing error" means? Is the angle error between a vector from the Earth to actual spacecraft position and a vector from the Earth to estimated spacecraft position?*

- In order to collect science data, the GRAIL spacecraft needed to accurately point the Ka-band antenna boresights towards the other spacecraft
- The portion of the pointing error budget allocated to navigation was 0.073º (1σ)
- The ephemeris pointing error is the difference between using a predicted ephemeris vs the actual ephemeris to point the spacecraft (e.g. the antenna) in any given direction
- The GRAIL Navigation Team was responsible for delivering the predicted spacecraft ephemerides to be uploaded to each spacecraft
- The frequency of ephemeris uploads was based upon how quickly the predicted accuracy exceeded the navigation error budget

Question 25

Spacecraft performance: Star tracker misalignment

- *During TLC Phase, the ACS team discovered a star tracker misalignment problem. Were you able to identify the misalignment by some measurement? Which measurement did you use? The star tracker's absolute calibration may need some ground control point. However, during TLC, there might be no reference to measure star tracker misalignment.*

- I don't know the answer to this question

Question 26

Navigation: Accelerometer telemetry

- *Accelerometer were not used for small thrusters. What was the usage of accelerometer for TLC Phase? After TCM, what was the main method to determine error between planned del-v and actual del-v? Accelerometer or orbit determination?*

- The accelerometer was used in larger maneuvers to determine when the desired ΔV had been achieved (i.e. "ΔV cutoff"). A timer was used as a backup.
- The accelerometer data (if available) was use to construct a force profile in the OD process (for estimate the maneuver parameters). The maneuver performance was then determined by OD process.
- The estimated maneuver parameters were used to improve / fine-tune the future maneuvers
- The accelerometer data can be used in the OD process, but it does not provide full information for the maneuver reconstruction

Question 27

Navigation: TCM-5 Go/No-Go Criteria

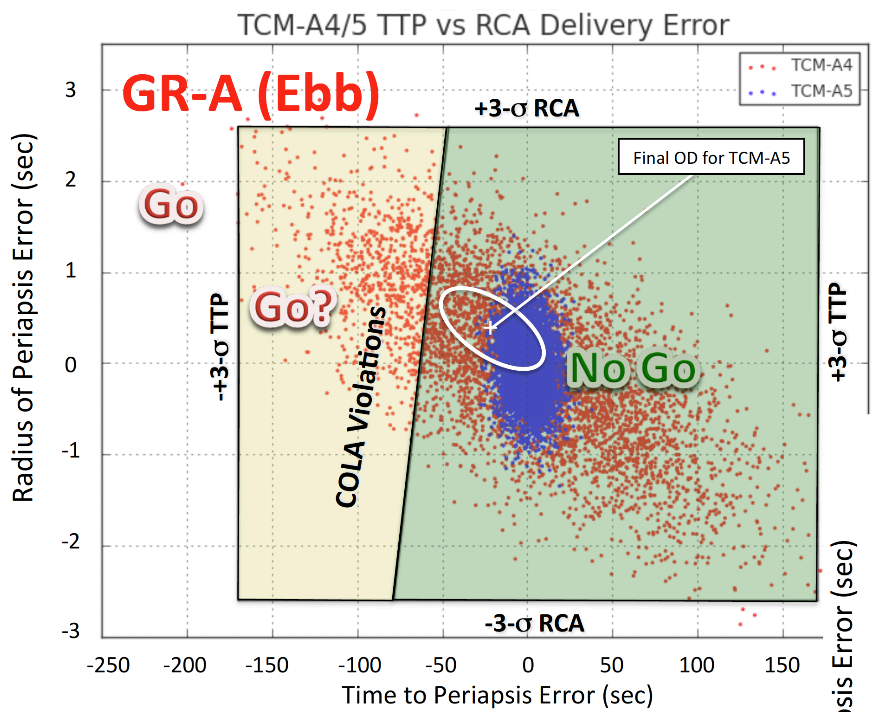
GRAIL
Discovery

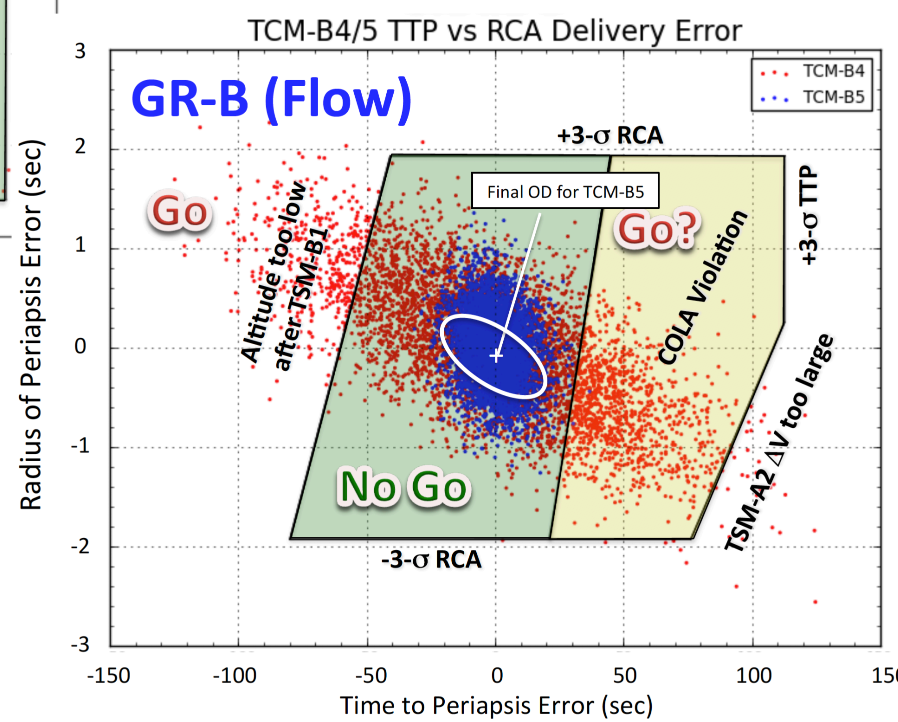
- *TCM-5 was cancelled due to good performance of the earlier TCMs. What was criteria of "good performance"? What was the specification and performance of del-v error?*

- To ensure that all the science requirements can be satisfied with TCM-5, must show $\pm 3\sigma$ TCM-5 values can be handled adequately
- To be able to cancel TCM-5, must show $\pm 3\sigma$ TCM-4 dispersions can be handled adequately — or, if some $\pm 3\sigma$ TCM-4 dispersions are too large, must establish some boundaries on those parameters
- Targeted LOI Parameters
  - SMA (semi-major axis), RCA (radius of closest approach), INC (inclination), LAN (longitude of the ascending node), AOP (argument of periapsis),
    TTP (time to periapsis)
  - The most critical delivery parameters were TTP and RCA
- Derived Requirements
  - Ensure no orbital crossing (i.e. COLA (collision avoidance) ≥ 10 km) while placing GRAIL-A and GRAIL-B into the science formation
  - LOI Phase: LOIs capture spacecraft into 11.5 hour orbits
  - OPR Phase: Two clusters of PRMs reduce periods to near science periods
  - TSF Phase: Max ΔV of each of the TSMs derived such that the execution error propagation does not exceed the expected limit for the formation

TCM-5 Go/No-Go Criteria – Bounding Boxes

GRAIL Discovery





TCM-A5 canceled
TCM-B5 canceled

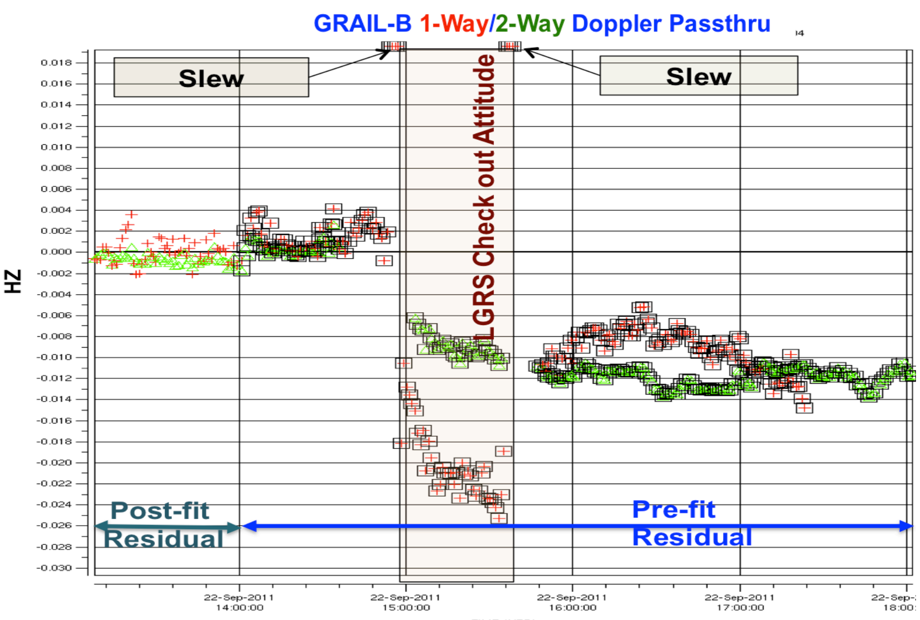
Question 28

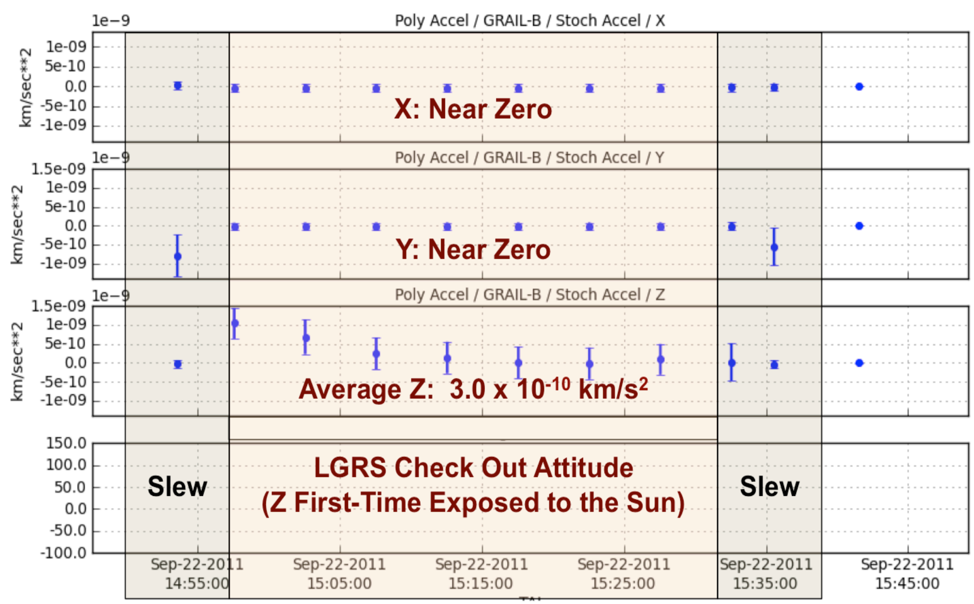
Navigation: Spacecraft outgassing

GRAIL
Discovery

- *Was the outgassing acceleration able to be measured by ranging and doppler measurement by the Earth ground station?*

- Yes, the effects of spacecraft outgassing were visible in the Doppler data
- No significant long-term outgassing was detected in the cruise attitude
  - Depleted to a ~10^{-12} km/s^2 level a few days after launch
- Outgassing events, at level of 10^{-9} km/s^2 were observed during non-cruise attitudes
  - Did not have a long-term impact due to short durations



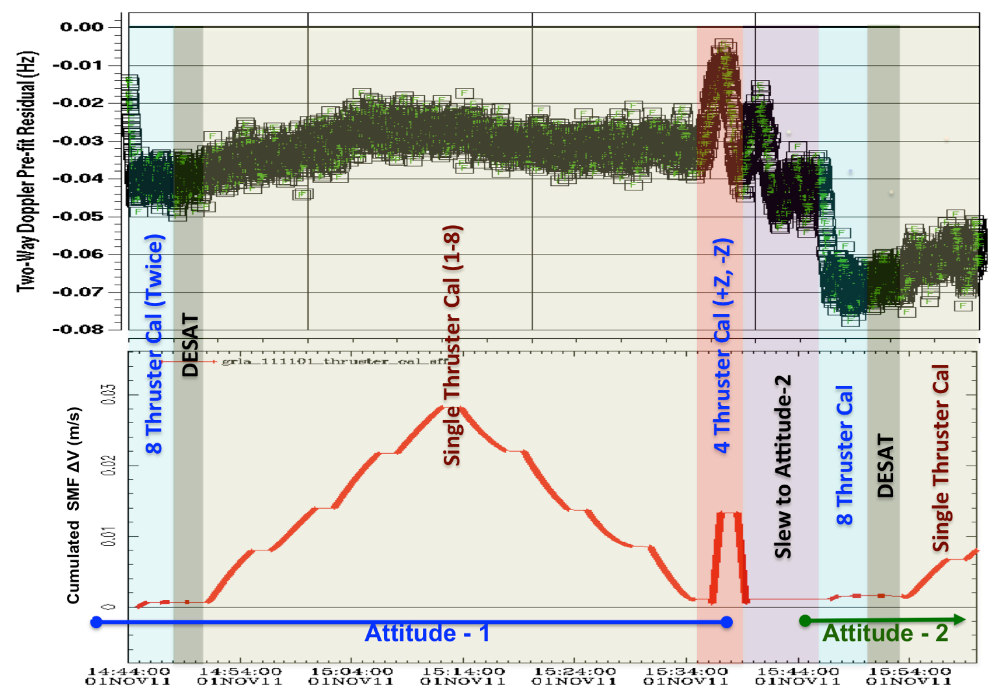


Question 29

Navigation: Thruster calibration

- *Does ACS thruster calibration generate delta-v? Did the trajectory design and maneuver planning consider the delta-v by thruster calibration?*

- Yes
- The GRAIL ACS system was designed as a “balanced system” – i.e. the thruster couples were designed to impart zero translational ΔV when changing attitude or managing reaction wheel speeds
- The thruster calibration was designed to characterize the thruster direction and output



Question 30

Spacecraft performance: Maneuver duration

- *In Table 6, resolution of burn duration seems 0.1 second. Is it right? Was there any issue of transient response of thruster valve?*

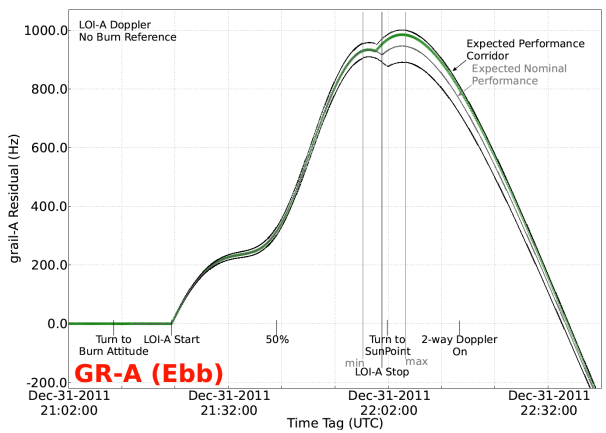
- The burn durations are reported to 0.1 second in Table 6, but I expect that spacecraft telemetry recorded the durations of the burns to a greater precision than that
- I do not know the details of the thruster hardware performance

Question 31

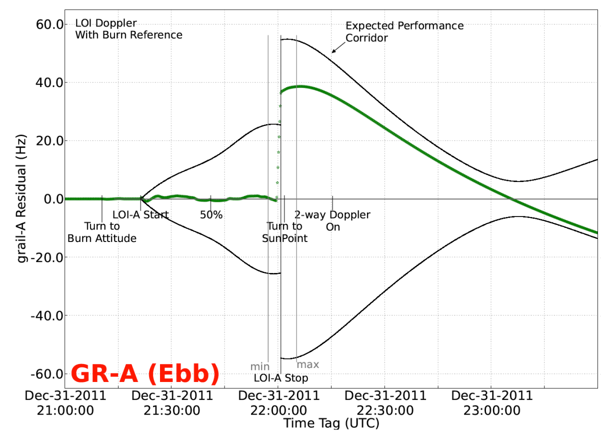
Spacecraft performance: Pointing error

- *In Table 6, pointing error is order of few mrad. What was the requirement of pointing error for TCM and LOI?*

- The standard maneuver execution error model includes both proportional and fixed, magnitude and pointing errors
- The parameters of the model vary according to maneuver and are based on things like the size of the maneuver (ΔV), the mode of the maneuver (e.g. duty-cycled), and if calibrations have already taken place
- The performance of LOI was not measured against a traditional pointing error model because the maneuver was performed as pitch-over maneuver



(a) LOI-A residuals with respect to the no-burn predicts



(b) LOI-A residuals with respect to the with-burn predicts

Question 32

Spacecraft performance: Maneuver implementation

- *TCMs were performed by main engine even required del-v is small. Wasn't any liquid settling burn (or propellant settling burn) to stabilize propellant and center of mass of spacecraft before main burn needed? If there was no settling burn, was there any issue about disturbance torque by center of mass variation?*

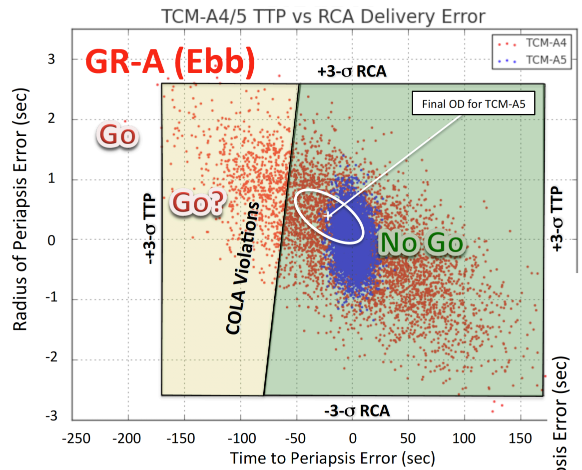
- I believe that a settling burn was incorporated into the maneuver execution, but I do not know the details of the burn implementation model

Question 33

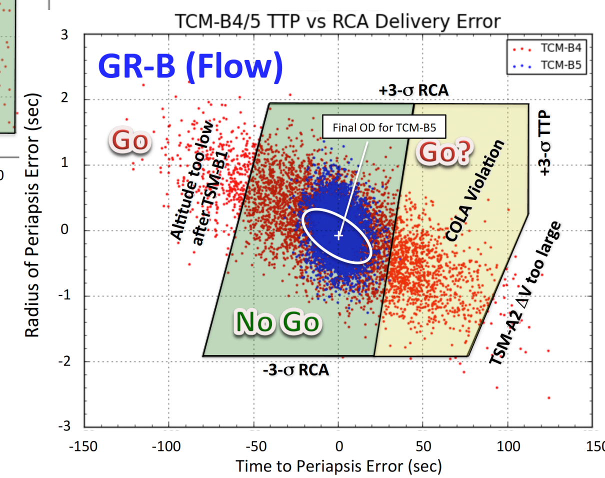
Navigation: TCM-5 Go/No-Go Criteria

- *Was the Go/No Go Criteria of TCM-5 required for science formation of GR-A and GR-B? If there is only one orbiter like KPLO, will the Go/No Go Criteria not be required or much loosen?*

- Yes, the TCM-5 Go/No-Go criteria were developed specifically for the GRAIL mission – with the goal of ensuring that the two spacecraft formation could be established
- Yes, the TCM-5 Go/No-Go criteria for a single spacecraft mission like KPLO would be expected to be simpler – and potentially looser



TCM-A5 canceled
TCM-B5 canceled



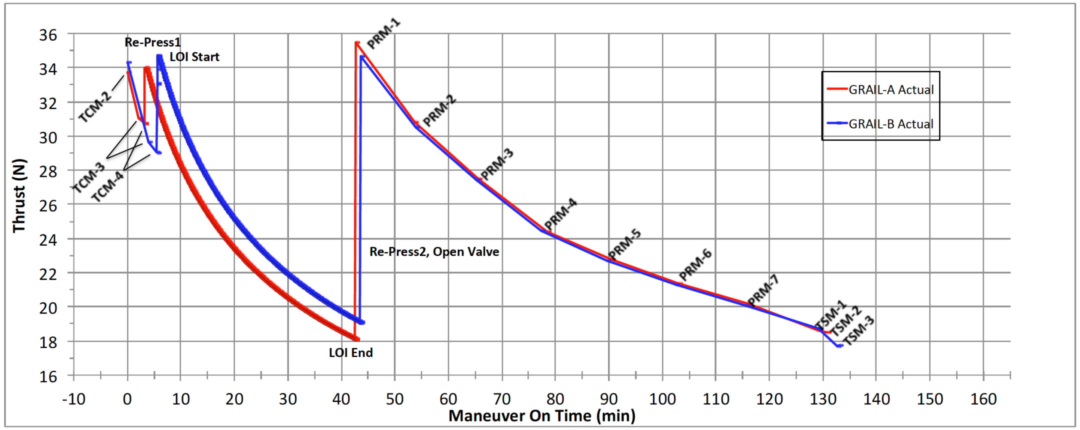
Question 34

Spacecraft performance: LOI strategy

GRAIL
Discovery

- *The propulsion system was blowdown mode. So re-pressurization was performed before and after LOI. Did you need the accelerometer because of blowdown mode? If pressure is regulated at constant pressure, is the timer cut-off enough for main engine burn?*

- Modeling the performance of the blowdown propulsion system was important to estimating maneuver performance on the GRAIL mission, but the accelerometer was not added solely for that reason
- In general, for all but the smallest maneuvers, using an accelerometer to cutoff a maneuver at the desired ΔV would be expected to be more accurate
- However, a pressure-regulated system generally has a higher and more predictable thrust and therefore a more predictable burn time



Question 35

Maneuver design: Delayed TCM

- *GRAIL had one day margin for maneuver execution. How many days can the margin for maneuver execution be extended? For example, if a planned TCM burn execution is missed, how soon should the recovery maneuver be performed?*

- Backup TCM Opportunities
  - Backup opportunities existed for all TCMs (on both GRAIL-A and GRAIL-B)
  - TCM-1: Backup scheduled (at least) 4 days after nominal
  - TCMs 2, 3, and 4: Backups scheduled one week after nominal TCM
  - TCM-5: Backup scheduled at LOI-3 days (nominal at LOI-8 days)

- Accommodating Launch Delays
  - TCM-1 and TCM-2 occur at a fixed time relative to launch
  - TCMs 3, 4, and 5 occur at a fixed time relative to LOI
  - TCMs 2 and 3 combined for launch dates "late" in the launch period due to shrinking TLC Phase timeline