The Gravity Recovery and Interior Laboratory Mission

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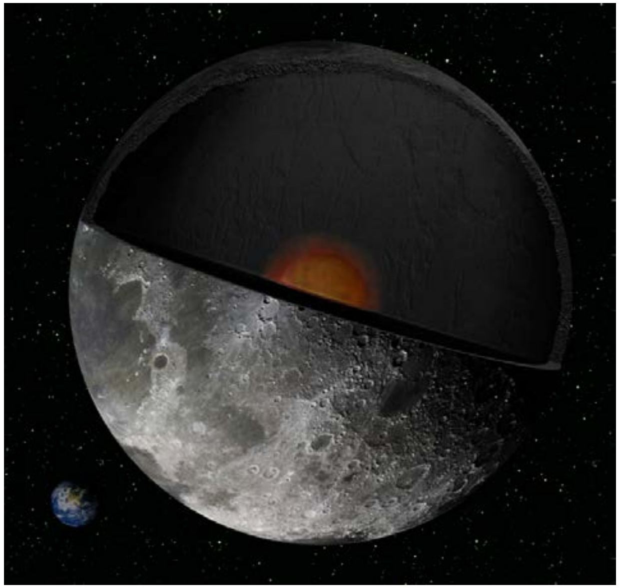
GRAIL Project Overview



Mission Objectives

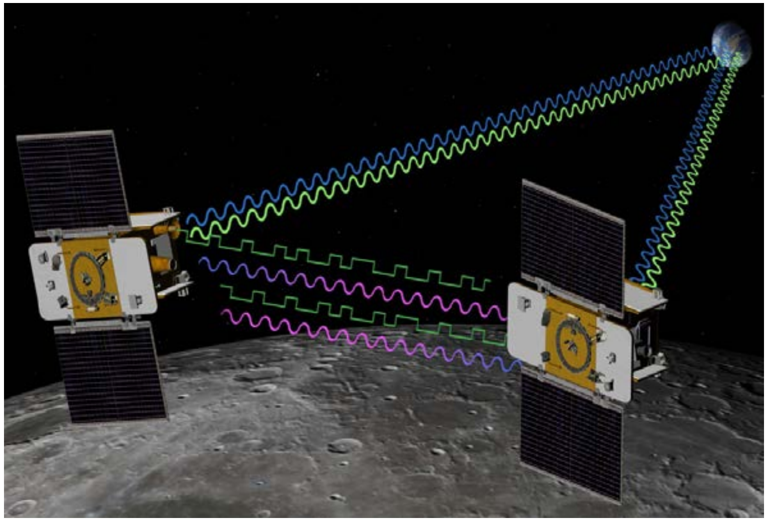
- Determine the structure of the lunar interior, from crust to core
- Advance understanding of the thermal evolution of the Moon
- Extend knowledge gained from the Moon to the other terrestrial planets

Other Features of the Mission

- Provides a global, high-resolution lunar gravity map
- Partnership by MIT, JPL. Lockheed Martin, GSFC, KSC and Sally Ride Science
- Carries cameras fully dedicated to education and public outreach
- First robotic demonstration of precision formation flying around another planetary body

Current GRAIL status:

- Twin spacecraft launched on Sept. 10, 2011 on a Delta-II Heavy from CCAFS
- Lunar orbit insertion: Dec. 31, 2011 (Ebb) & Jan. 1, 2012 (Flow)
- Science mapping started on Mar. 5, 2012 and the prime mission was completed on May 29 (89 days)
- Extended mission completed on Dec. 17



GRAIL launched on schedule, on cost and on spec

Primary Mission Science Objectives

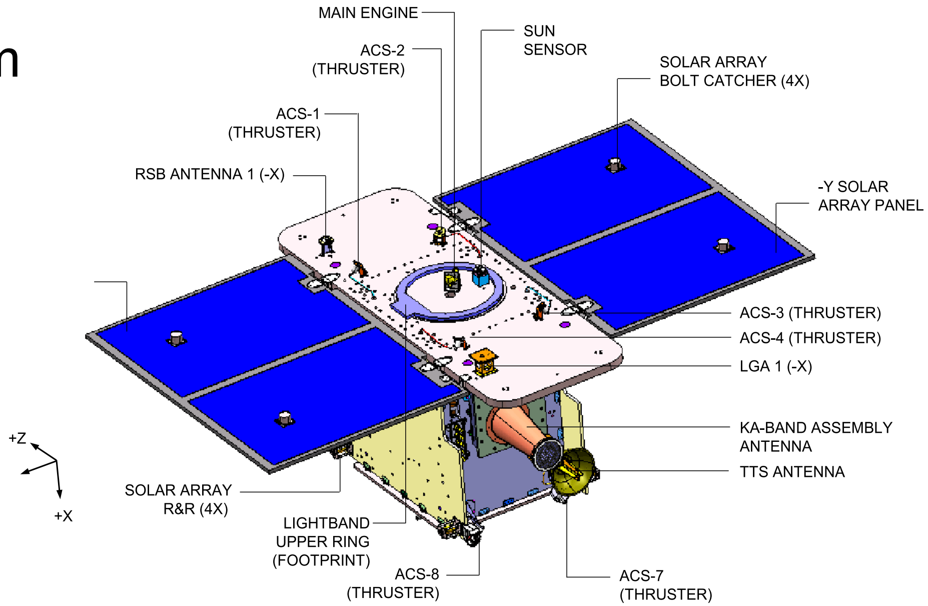
Science Objectives	Science Investigations	Area ($10^6 km^2$)	Resolu-tion (km)	Requirement (30-km block)*	Full Science Requirements	Minimum Science Requirements
Determine the structure of the lunar interior	1. Crust & Lithosphere	~10	30	± 10 mGal	Completed 5/2012 (due 6/2013)	Completed 5/2012 (due 6/2013)
	2. Thermal Evolution	~4	30	± 2 mGal	Completed 5/2012 (due 6/2013)	Completed 5/2012 (due 6/2013)
	3. Impact Basins	~1	30	± 1 mGal	Completed 5/2012 (due 6/2013)	Completed 5/2012 (due 6/2013)
	4. Magmatism	~0.1	30	± 0.1 mGal	Completed 5/2012 (due 6/2013)	Completed 5/2012 (due 6/2013)
Advance understanding of the thermal evolution of the Moon	5. Deep Interior	N/A	N/A	$k_2 \pm 6x10^{-4}$ (3%)	Work in Process (due 6/2013)	N/A
	6. Inner Core Detection	N/A	N/A	$k_2 \pm 2.2x10^{-4}$ (3%) $c_{21} \pm 1x10^{-10}$	Work in Process (due 6/2013)	N/A

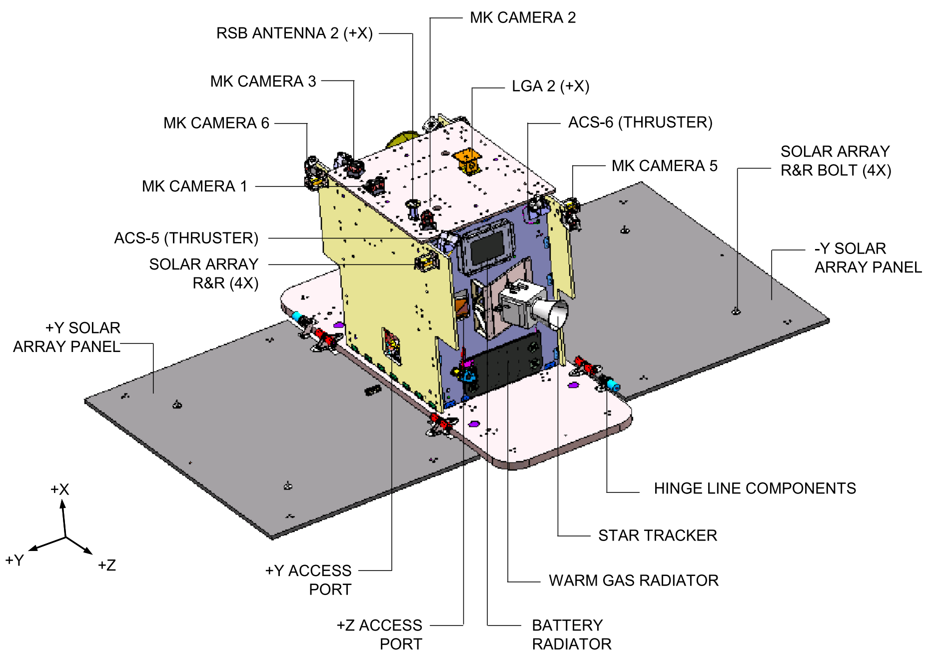
* 1 Gal or Galileo is the measure of acceleration and is defined in SI units as .01 m/sec^2; a mGal is ~1 µg.

The GRAIL minimum science requirements were achieved a year ahead of schedule

GRAIL Spacecraft Views

- Spacecraft based on heritage from XSS-11 (main structure and propulsion) and MRO (avionics, fight software, power)
- Spacecraft launch mass: 306 kg including 108 kg of fuel





- The spacecraft are 3-axis stabilized with reaction wheels and 1-N hydrazine ACS thrusters for attitude control, and a star tracker and IMU for attitude determination
- A 22-N hydrazine main engine provides thrust for all maneuvers, except for small orbit trim maneuvers that use the ACS thrusters

Spacecraft Acoustic Test

Spacecraft Solar Array Test

Spacecraft Thermal-Vacuum Test

GRAIL was Shipped to Florida in May 2011

The GRAIL S/C was shipped 1-week earlier than the original plan

NASA Deputy Administrator Garver Visiting GRAIL at the Cape

GRAIL PI the night before launch

September 10, 2011 @ 9:08 am EDT—a Great Day for the GRAIL Team

GRAIL Development Challenges

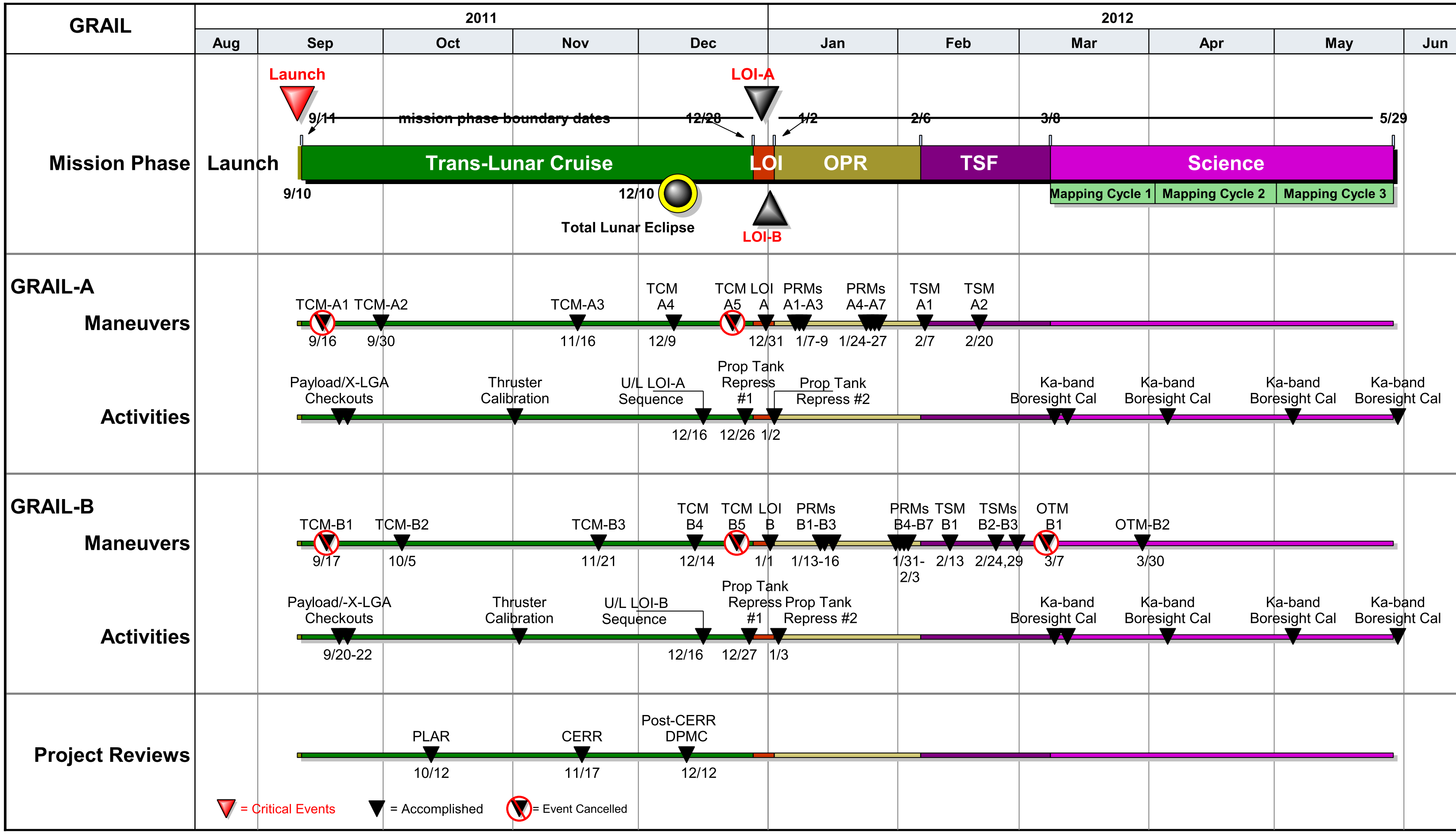
#	Key Development Challenge	GRAIL Method to Overcome Challenge
1	Late identification and ordering of long-lead payload parts	A parts acquisition tiger team was established consisting of engineers, parts specialists, and procurement personnel. The parts were delivered when needed, and the payload was delivered 3 weeks early.
2	Difficulty in transitioning an advanced research development into flight avionics	This was the #1 issue of the project. The flight avionics was delivered approximately 6 months late and required a major team effort to overcome numerous manufacturing issues. Ultimately, the long delay in avionics delivery did not delay the GRAIL launch.
3	Incorrect launch loads uncovered after Project CDR	This required the addition of a load attenuation ride system requiring the expense of ~$1M, but it did not impact schedule margin.
4	Reaction wheel development issues related to a loss of preload during qual testing	A tiger team was put in place to update the design and to develop an adequate test program. The delay in delivering the reaction wheels had no impact on the overall project schedule.

NASA Administrator Bolden Visiting the GRAIL MSA

The GRAIL flight team successfully completed its prime science mission on 5/29/2012

Prime Mission Schedule

8-13-2012 V1

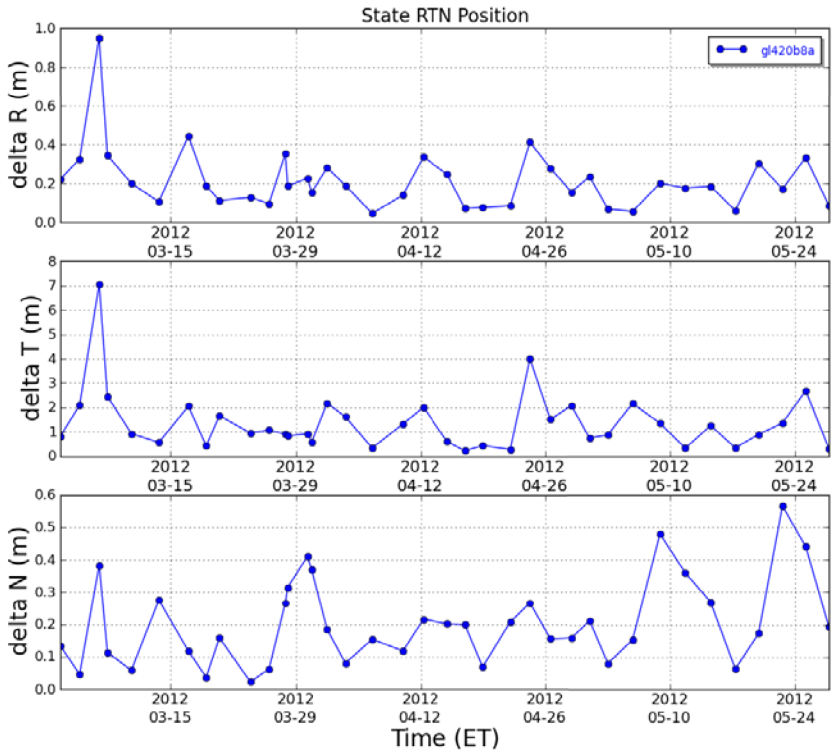


28 maneuvers performed flawlessly to achieve science orbits

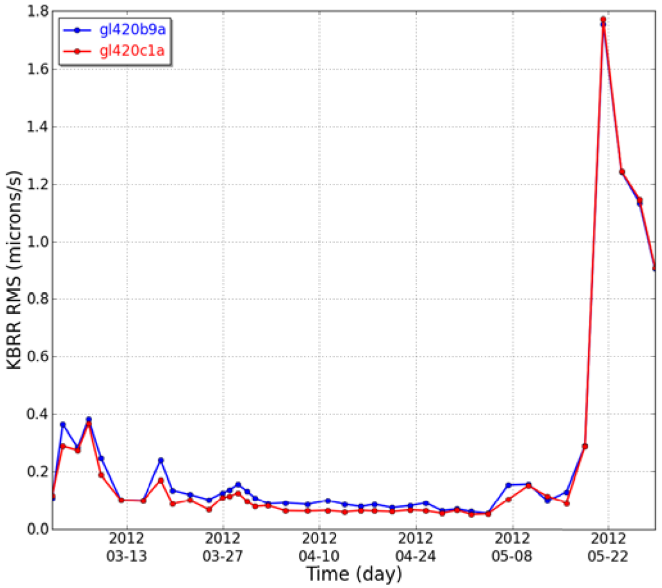
GRAIL Science Data Analysis

- The GRAIL payload **measures the change in the relative motion** between the two orbiters.
- The change in the relative speed is used to determined the lunar gravity field (technique similar to GRACE mission).
- Data acquisition: 637 Mbytes of data or **>99.99% of possible data**
- A high-resolution lunar gravity field is currently available to degree and order 420; corresponds to **~13 km blocksize surface resolution**.
- Out of 6 total science requirements, investigations 1-4 are satisfied (i.e., high-resolution lunar gravity map) and are 2 to 3 times an order of magnitude improved from previous maps.
- Currently working on investigations 5 & 6, i.e., deep interior (lunar tides) and detection of core motion relative to mantle.

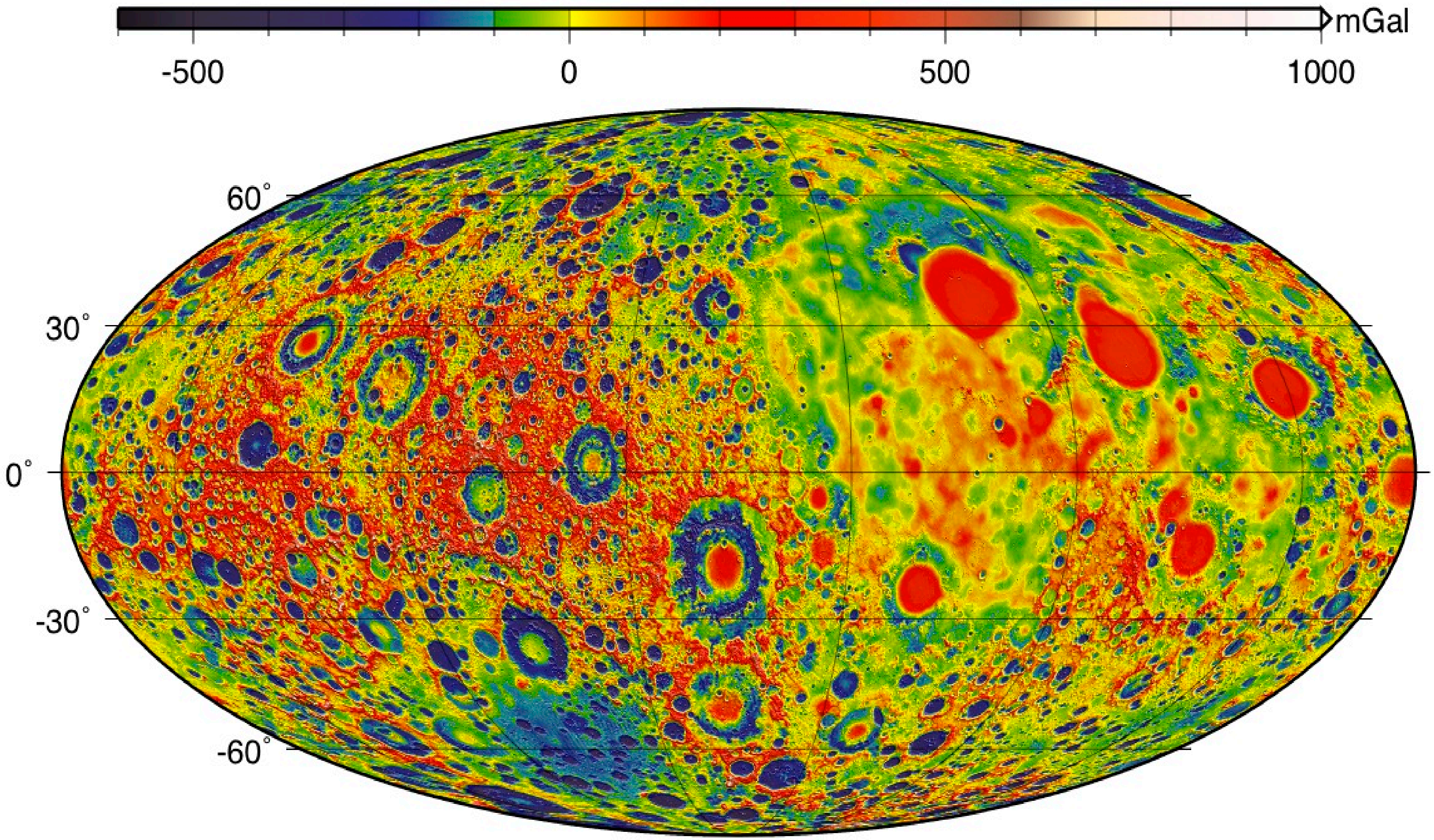
GRAIL Trajectory Overlap RMS



GRAIL KBR RMS Fits



Free-air gravity GL0420A

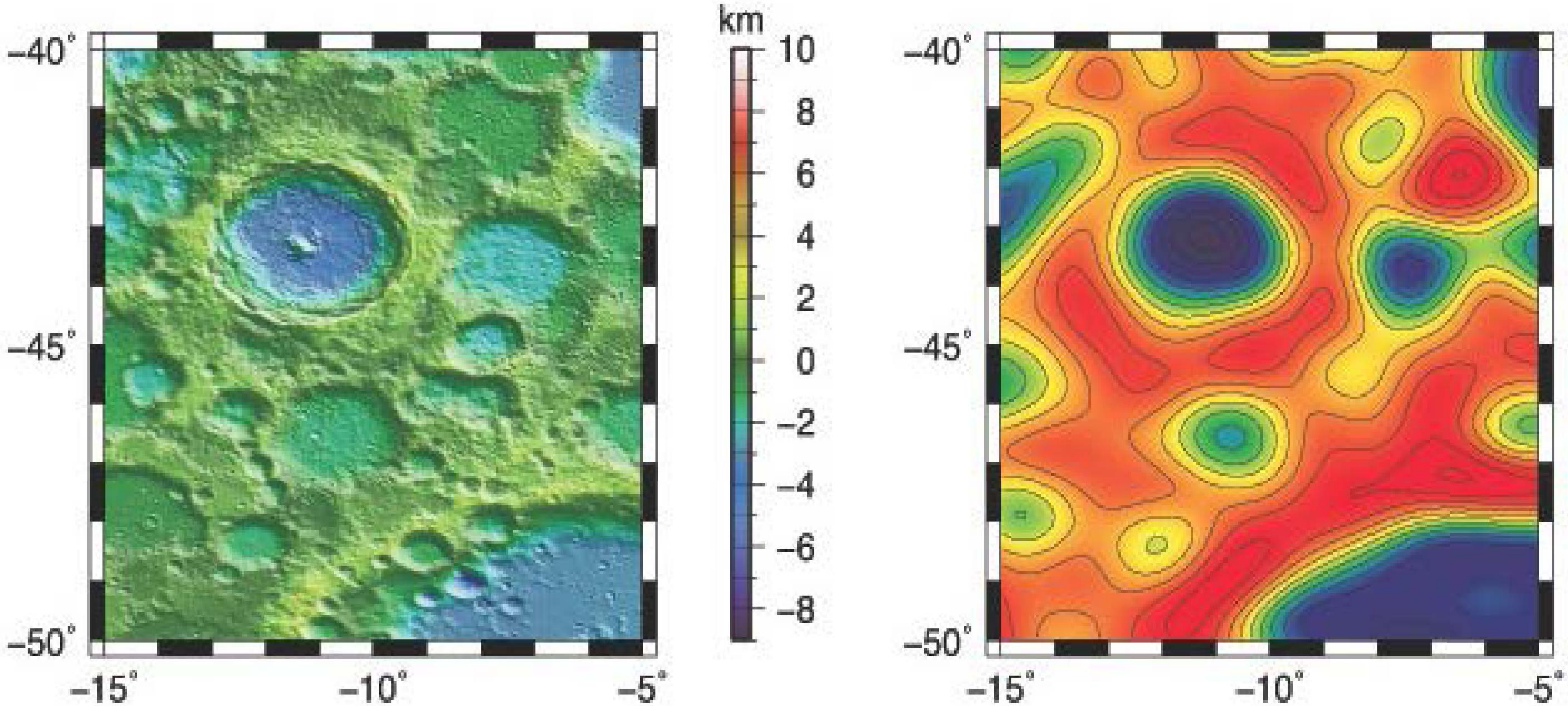


Zuber et al. [2012]

NASA/GSFC/MIT/LRO/LOLA

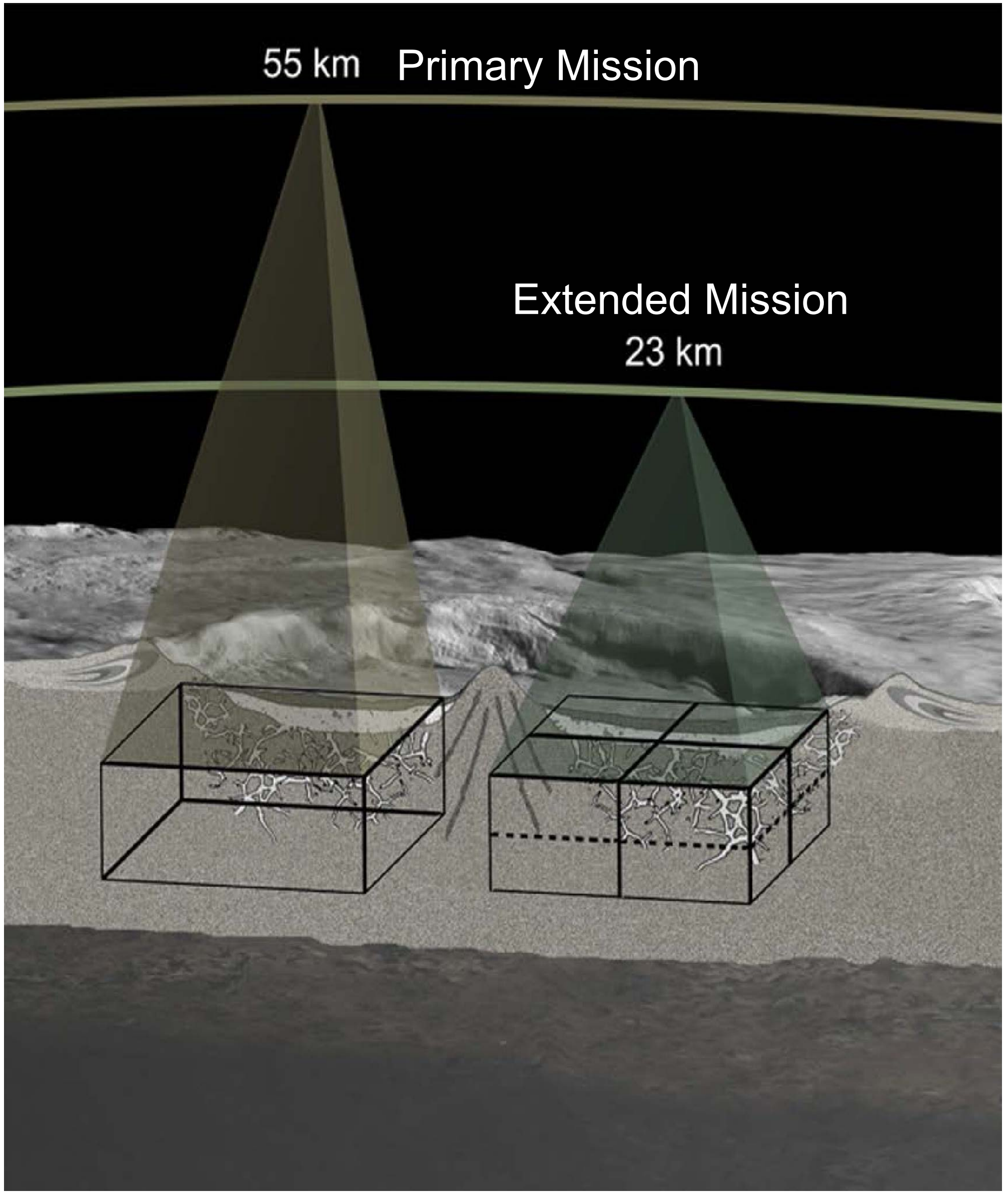
NASA/MIT/JPL/GRAIL

Tycho – LOLA Topography compared to GRAIL gravity



Tycho, a prominent 86-km diameter complex crater on the Moon's nearside, is shown in LOLA topography (left) from LRO and GRAIL gravity (right). Tycho is in the upper left of each figure. In the gravity map reds correspond to mass excesses and blues to mass deficits.

XM Science Objective and Investigations

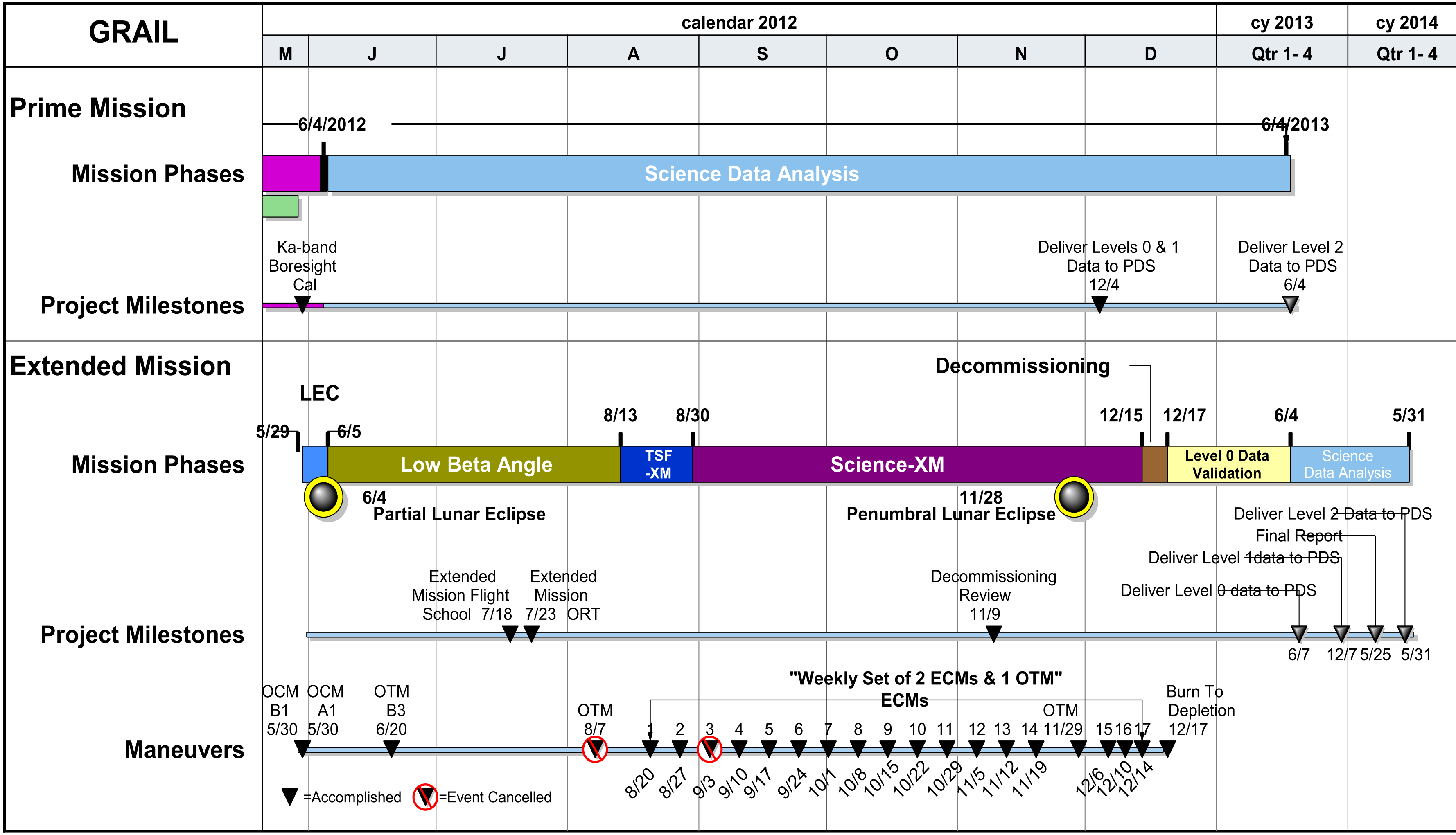


NASA/MIT/JPL/GRAIL

- GRAIL XM objective:
  – Determine the structure of lunar highland crust and maria, addressing impact, magmatic, tectonic and volatile processes that have shaped the near surface
- GRAIL XM investigations:
  1. Structure of impact craters
  2. Near-surface magmatism
  3. Mechanisms and timing of deformation
  4. Cause(s) of crustal magnetization
  5. Estimation of upper-crustal density
  6. Mass bounds on polar volatiles

Extended Mission Timeline

1-25-2013 v1



The submitted XM proposed science phase ended on 12/3/12, but the actual science phase was extended through 12/15/12

GRAIL Operations Challenges

#	Key Operations Challenge	GRAIL Impact and Resolution
1	Operating during high solar activity revealed vulnerability of E/PO MoonKAM	MoonKAM power supplies latched up at higher currents and had to be power-cycled. In one instance, specific conditions produced a dangerous oscillation that damaged spacecraft switches when powering off the unit. As a result, MoonKAM operations were largely suspended during the Extended Mission.
2	Telecommunications multipath resulted as uplink and downlink signals reflected off the Moon's surface	During certain orbit geometries, multipath resulted in lost data and uplink errors. With lower altitudes, the frequency of multipath increased. The operations teams developed strategies to recover from multipath outages, including retransmission of lost data and resending failed commands.
3	Errors in orbit determination solutions were increasingly driven by the fidelity of gravitational models of the Moon during low-altitude science orbit	Use of models from previous missions resulted in higher uncertainty in orbit solutions. Use of GRAIL gravity models provided by the science team allowed the navigation team to continuously improve solutions as the mission progressed. High-order Primary Mission gravity models allowed the even lower-altitude Extended Mission to proceed much more smoothly as a result.

EPO MoonKAM Imaging of the Moon

- This image of the Hercules Crater and was requested by students from the following:
  - Remington Middle School in Massachusetts
  - State Astronomy Club in Zaporozhye, Ukraine
  - St. Cronan's Boys National School in Bray, Ireland

GRAIL's MoonKAM returned over 120,000 lunar surface images, and over 100,000 students in over 2,800 middle schools participated in the program.

Summary

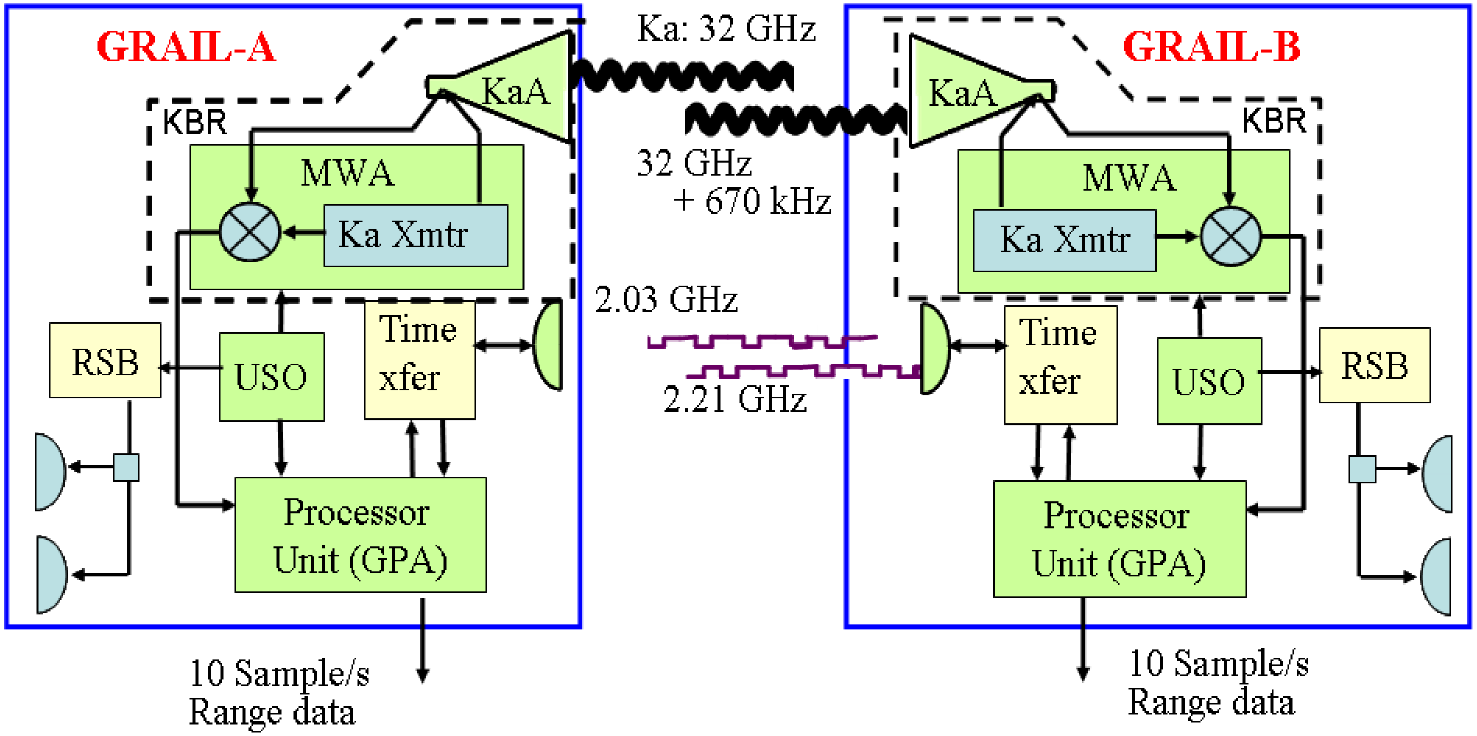
- GRAIL successfully completed its Prime and Extended Mission on schedule and under budget
- During its 15-month mission, the mission operations team successfully implemented 78 maneuvers
- Achieved project minimum mission success criteria for the Prime Mission in May 2012, one year ahead of schedule (Investigation 1–4)
- Science data volume at end of Prime Mission: 637 Mbytes (>99.99% of possible data)
- Various engineering demos were successfully conducted between Dec. 14 and Dec. 17
  - GR-A MoonKAM demo
  - 3-axis reaction wheel ACS operations demo
  - Velocity point ACS operations demo
  - Propellant gauging study
  - Burn-to-depletion maneuver
- Lunar impact and mission completion on Dec. 17

GRAIL's data set has generated the highest-resolution gravity map of any celestial body

Back Ups

LGRS Block Diagram

- GRAIL's Lunar Gravity Ranging System (LGRS) is based on GRACE-heritage science instrument which has been mapping the gravity of Earth since March 2002
- Key measurement is the Line Of Sight (LOS) range-rate made with to an accuracy of 4.5 micron/sec over a 5-second sample interval



LGRS was delivered to the spacecraft 3-weeks ahead of schedule