GRAIL: Facilitating Future Exploration of the Moon

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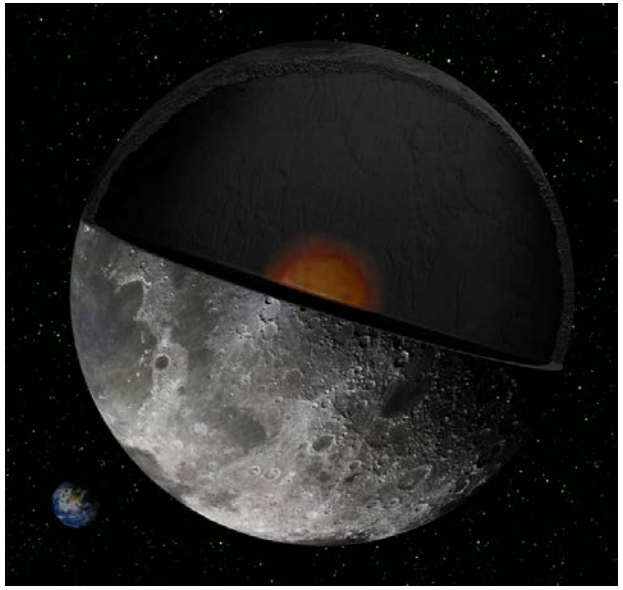
GRAIL Project Overview



Mission Objectives

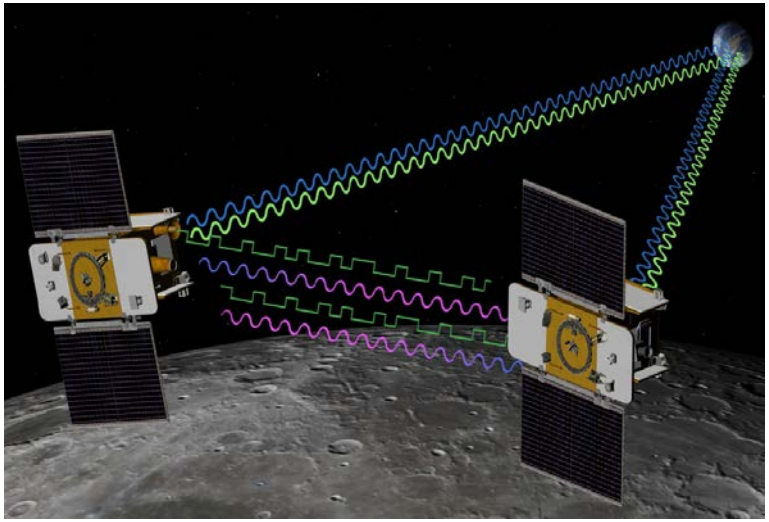
- Determine the structure of the lunar interior, from crust to core
- Advance understanding of the thermal evolution of the Moon
- Extend knowledge gained from the Moon to the other terrestrial planets

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 from June 2012 through Dec. 2012



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	$\pm$ 10 mGal	Completed 5/2012 (due 6/2013)	Completed 5/2012 (due 6/2013)
	2. Thermal Evolution	~4	30	$\pm$ 2 mGal	Completed 5/2012 (due 6/2013)	Completed 5/2012 (due 6/2013)
	3. Impact Basins	~1	30	$\pm$ 1 mGal	Completed 5/2012 (due 6/2013)	Completed 5/2012 (due 6/2013)
	4. Magmatism	~0.1	30	$\pm$ 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	$k_2 \pm 6 \times 10^{-4}$ (3%)	Work in Process (due 6/2013)	N/A
	6. Inner Core Detection	N/A	N/A	$k_2 \pm 2.2 \times 10^{-4}$ (3%) $c_{21} \pm 1 \times 10^{-10}$	Work in Process (due 6/2013)	N/A

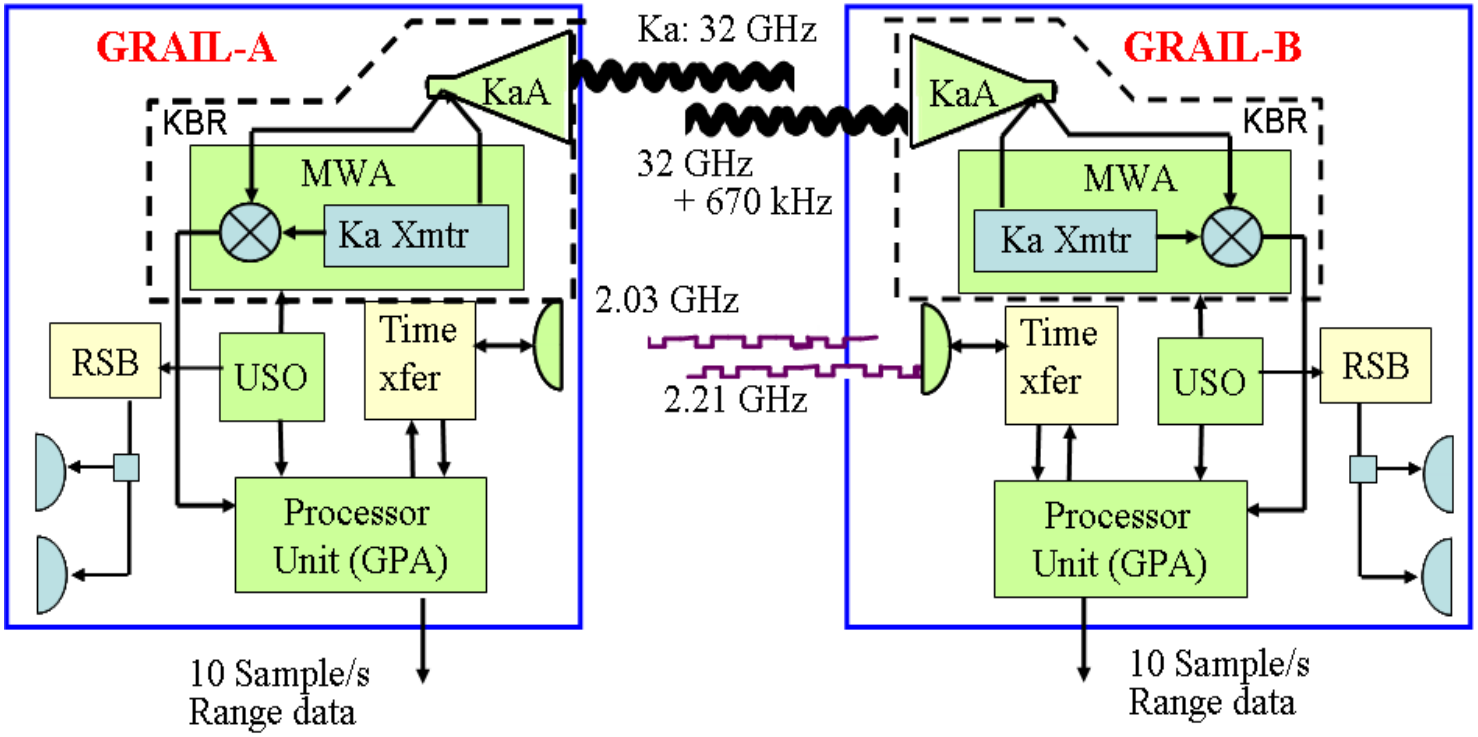
* 1 Gal or Galileo is the measure of acceleration and is defined in SI units as .01 m/sec^2; a mGal is ~1 µg.

Summary of Key GRAIL Events

Event	Date
GRAIL Selection as a Discovery Mission	Dec. 2007
Preliminary Design Review	Nov. 2008
Confirmation Review	Jan. 2009
Critical Design Review	Nov. 2009
Systems Integration Review	June 2010
Pre-Ship Review	May 2011
Orbiters delivered to Cape	May 2011
Launch	Sept. 10, 2011
Lunar Orbit Insertion	Dec. 31, 2011 (Ebb)/Jan. 1, 2012 (Flow)
Primary Science Phase Began	March 2012
Primary Science Phase Ended	May 2012
Extended Science Phase Ends	December 2012

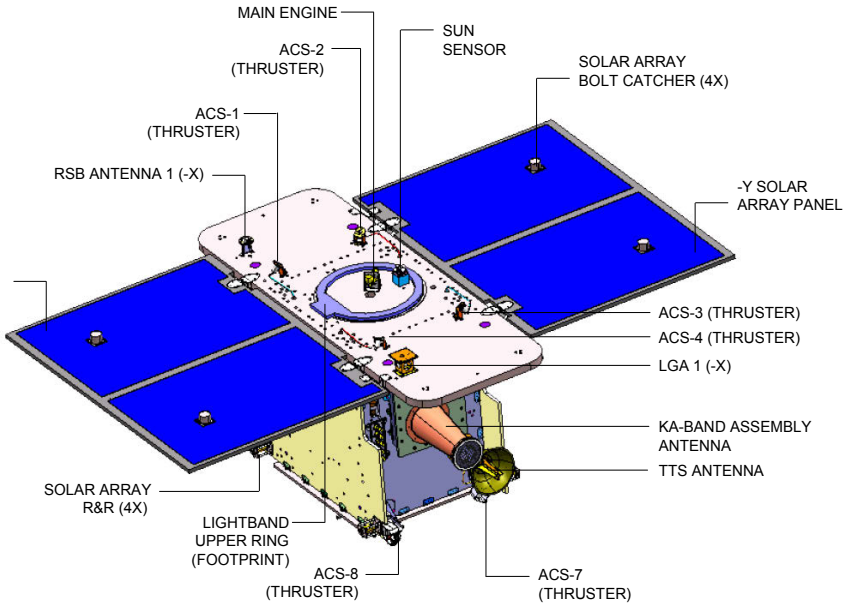
LGRS Block Diagram

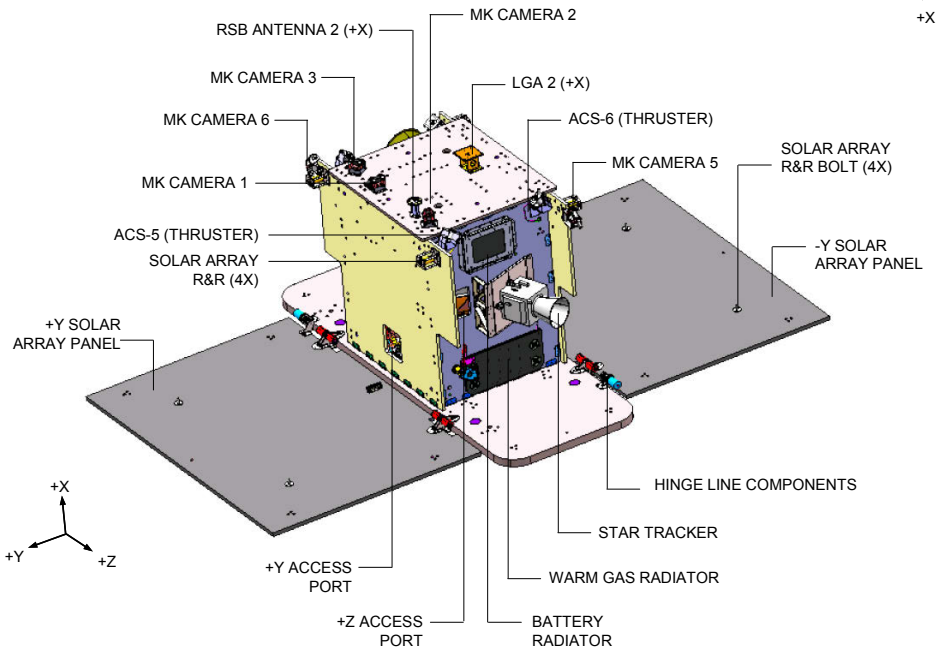
- GRAIL's Lunar Gravity Ranging System (LGRS) is based on GRACE-heritage science instrument which has been mapping the gravity of Earth since March 2002
- Key measurement is the Line Of Sight (LOS) range-rate made with an accuracy of 4.5 micron/sec over a 5-second sample interval



GRAIL Spacecraft Views

- GRAIL's twin spacecraft were built by LMSS and are largely single-string
- Spacecraft based on heritage from XSS-11 (main structure and propulsion) and MRO (avionics, fight software, power)





Spacecraft Acoustic Test

Spacecraft Solar Array Test

Spacecraft Thermal-Vacuum Test

GRAIL was Shipped to Florida in May 2011

NASA Deputy Administrator Garver Visiting GRAIL at the Cape

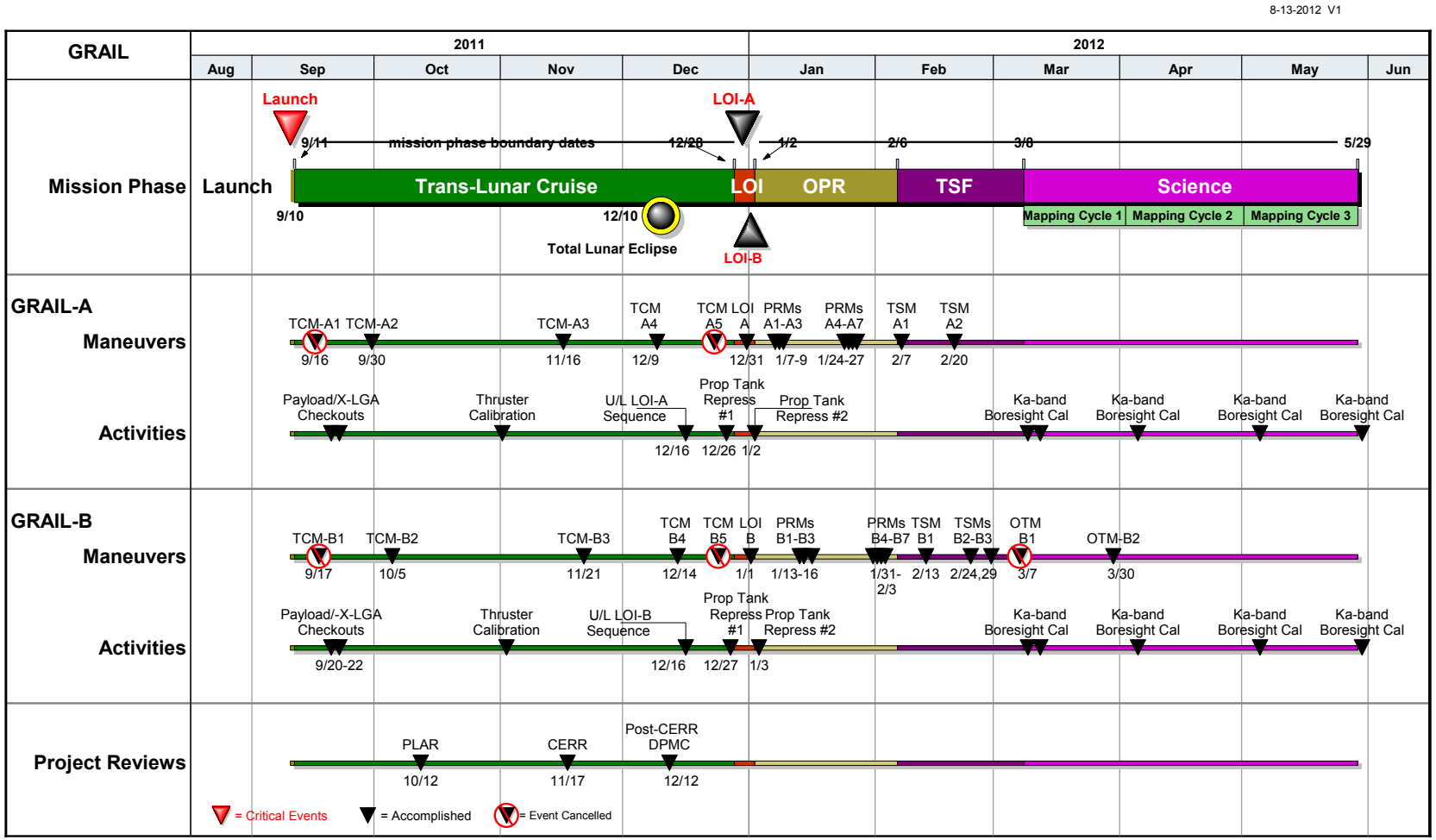
GRAIL PI the day before launch

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

NASA Administrator Bolden Visiting the GRAIL MSA

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

Prime Mission Schedule

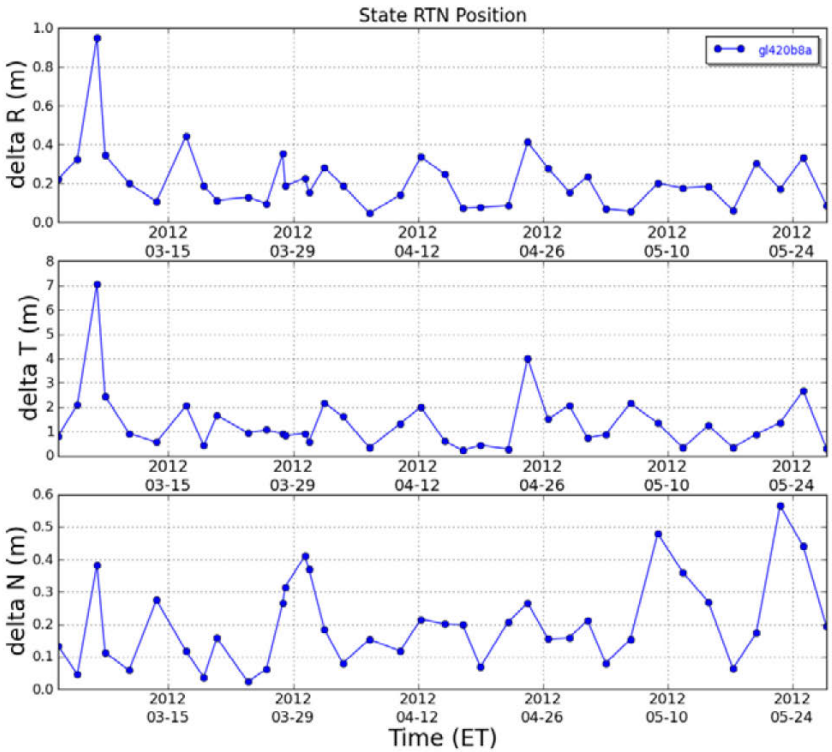


28 maneuvers performed flawlessly to reach science orbits

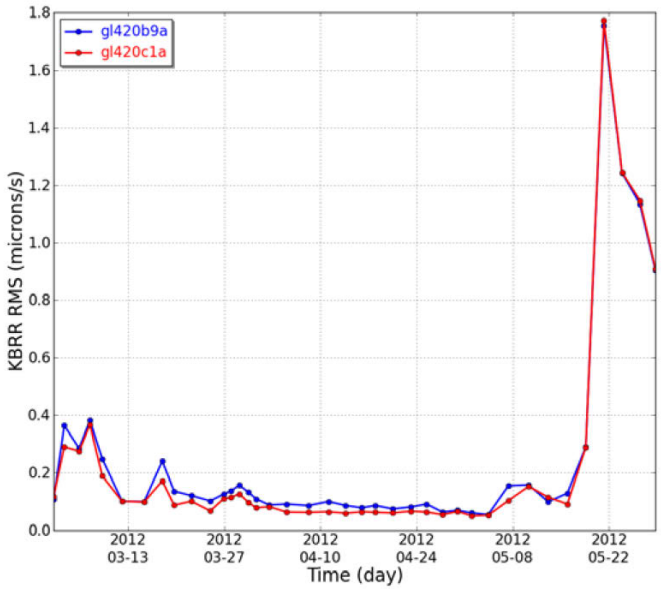
GRAIL Science Data Analysis

- 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.

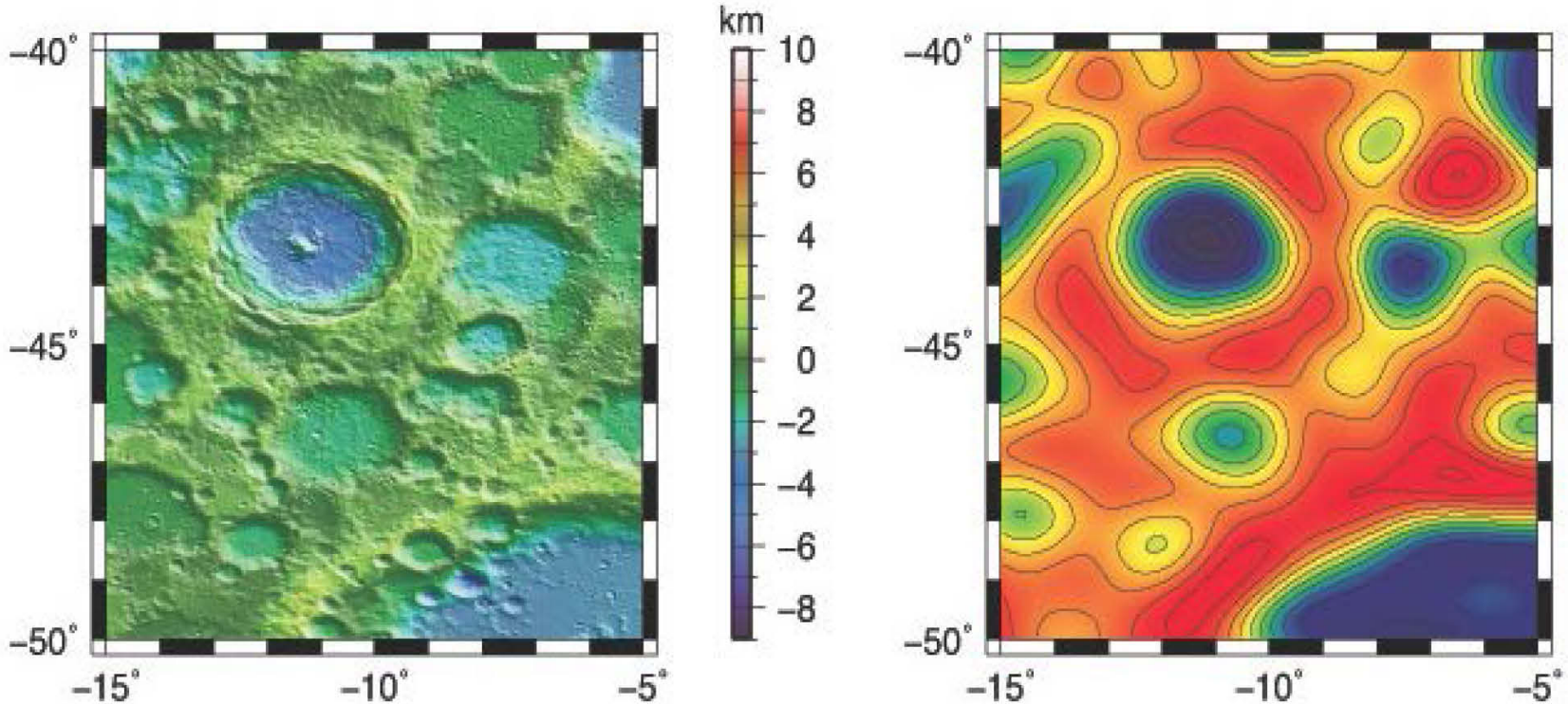
GRAIL Trajectory Overlap RMS



GRAIL KBR RMS Fits



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.

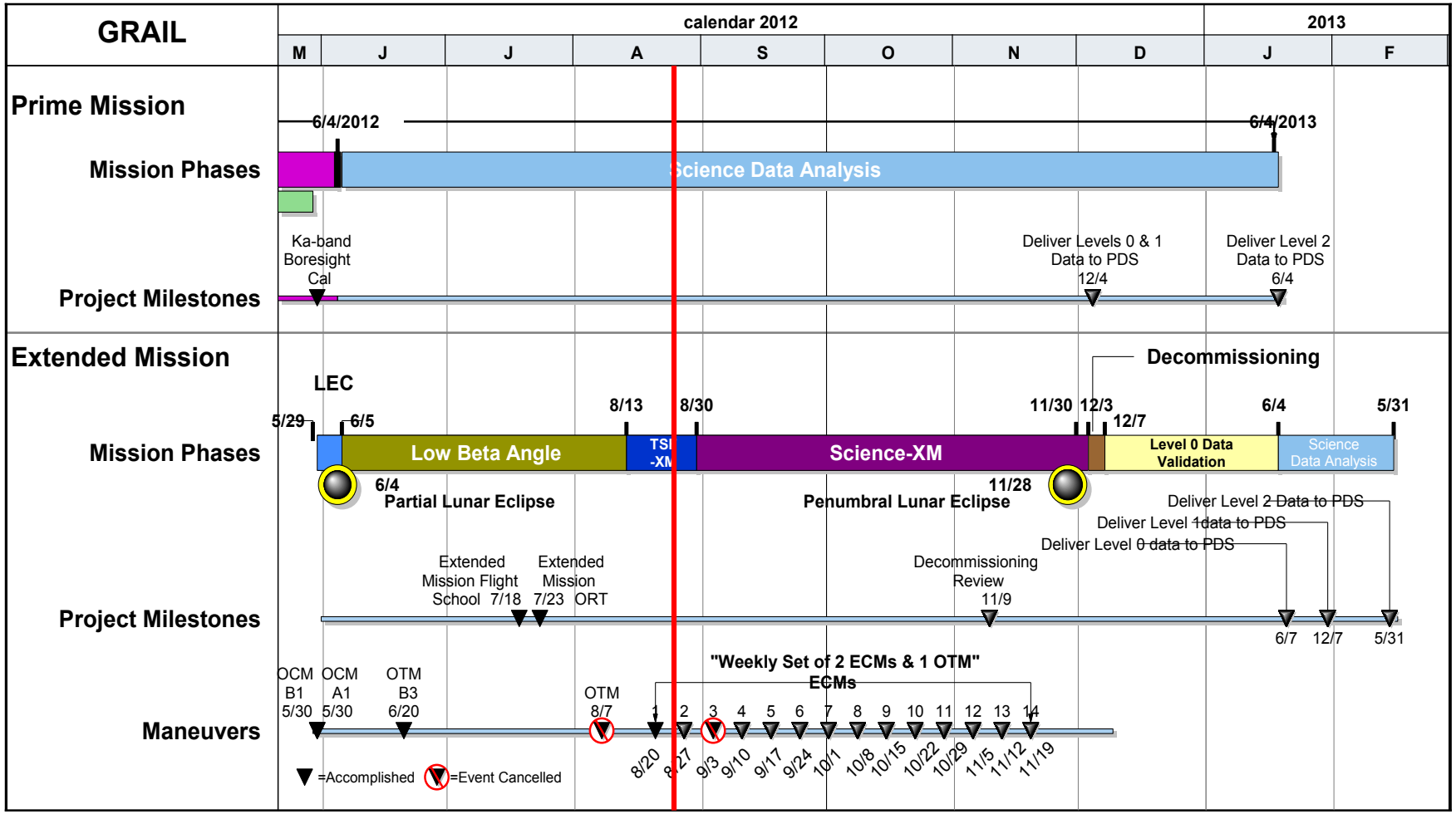
Extended Mission Science Objectives

- GRAIL's extended mission will deliver geophysics at the scale of surface geology
- Objective is to determine the structure of lunar highland crust and maria, addressing impact, magmatic, tectonic and volatile processes that have shaped the near surface

Investigation	Spatial Scale & Accuracy Reqt
Structure of impact crates	12 km, 0.02 mGal
Near-surface magmatism	30 km, 0.01 mGal
Mechanisms and timing of deformation	12 km, 0.005 mGal
Cause(s) of crustal magnetization	12 km, 0.002 mGal
Elimination of upper crustal density	12 km, 0.005 mGal
Mass bounds on polar volatiles (assumes a 10-m-thick layer composed of 5% H_2O ice, 95% regolith)	30 km, 0.002 mGal

Extended Mission Schedule

8-22-2012 v1



Facilitating Future Exploration of the Moon

- GRAIL's high-resolution, global gravity field eliminates gravity uncertainties for precision lunar navigation and landings for all future robotic and human science and exploration missions
- GRAIL's gravity model is already being used by NASA's LRO to improve navigation and will be provided to NASA's LADEE project for its upcoming mission to the Moon
- Other possible uses of GRAIL's data
  - Identification of lava tubes for human habitat for use during periods of high solar radiation
  - Identification of subsurface ice to support human habitation
  - Support identification of future landing sites for exploration

Summary

- GRAIL successfully completed its Prime Mission on schedule and under budget
- 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)
- Spacecraft successfully transited the partial lunar eclipse of 6/4/12
- Currently preparing for Extended Mission data gathering at very low altitude (23 km)

GRAIL's data set is already being used to facilitate current and future exploration of the Moon