To the Moon - an Overview of the GRAIL Project and Some Lessons Learned

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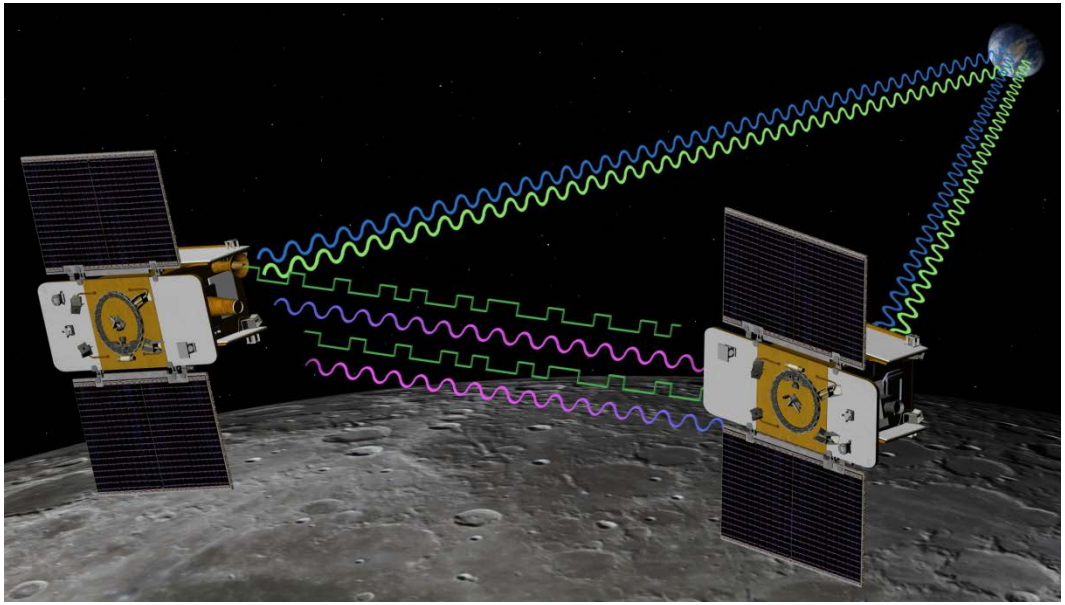
Mission Overview

Science Objectives:

- Determine the structure and interior of the Moon, from crust to core
- Understand the thermal evolution
- Extend knowledge to other terrestrial planets

Mission Outline:

- Twin S/C launched on a KSC-provided Delta 2920H-10
- Prime mission (PM) of 9 months followed by Extended Mission (XM) of 6 months
- Low altitude, polar orbit



Science Measurements & Payload:

- Ka-band ranging system measures relative velocity of the CM of the 2 spacecraft
- DSN used for absolute position determination

Mission Management:

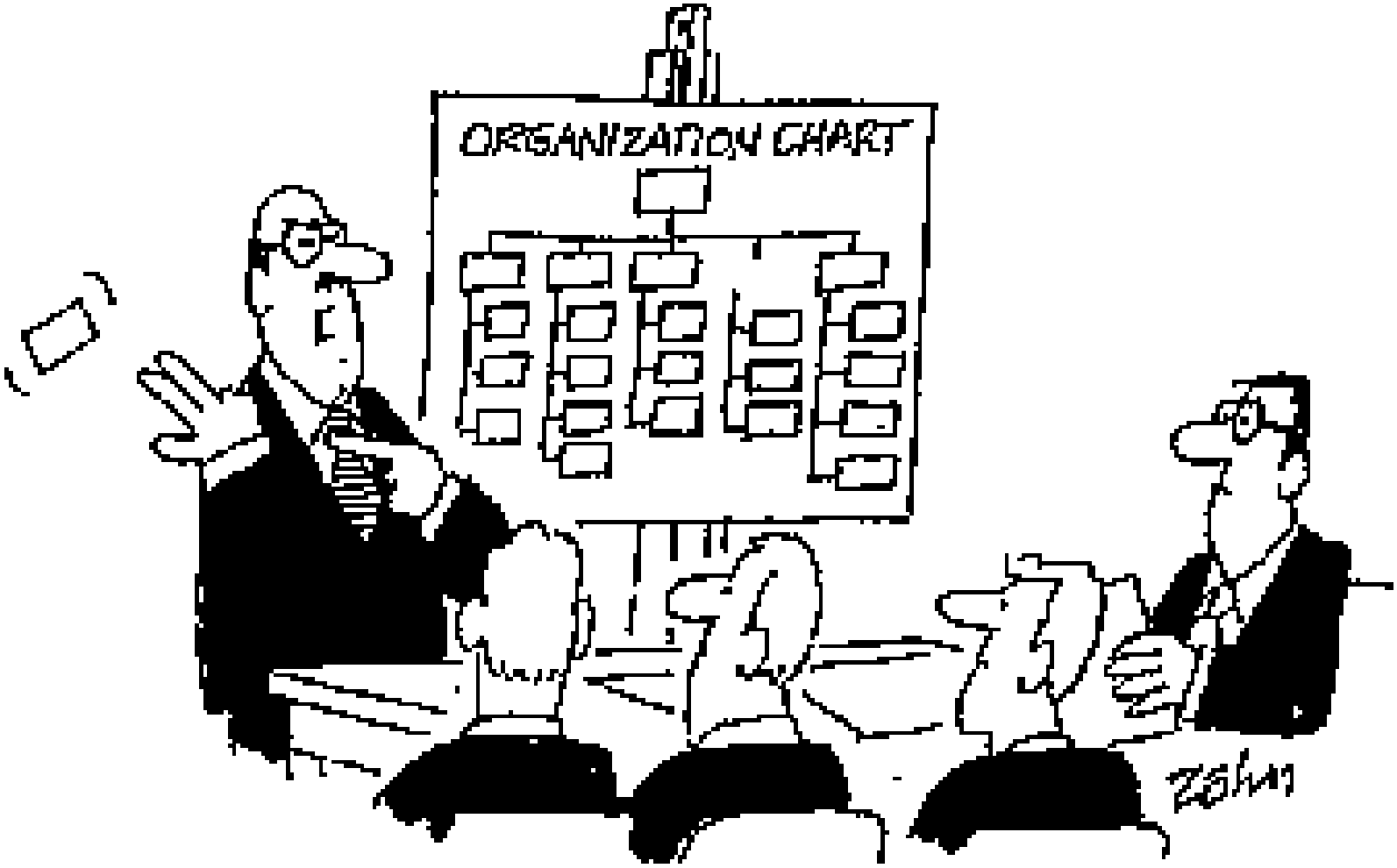
- MIT: Principle Investigator, SRS contract for E/PO
- JPL: Project Management, Payload and Mission operations
- Lockheed Martin: Spacecraft and Mission Operations Support

Schedule and Cost:

- Launched in Sep 2011 with PM completed in May 2012 and XM completed in Dec. 2012
- Cost cap of $485M for PM + XM

Level-1 requirements were unchanged since proposal submission

This is not the GRAIL Organization Chart



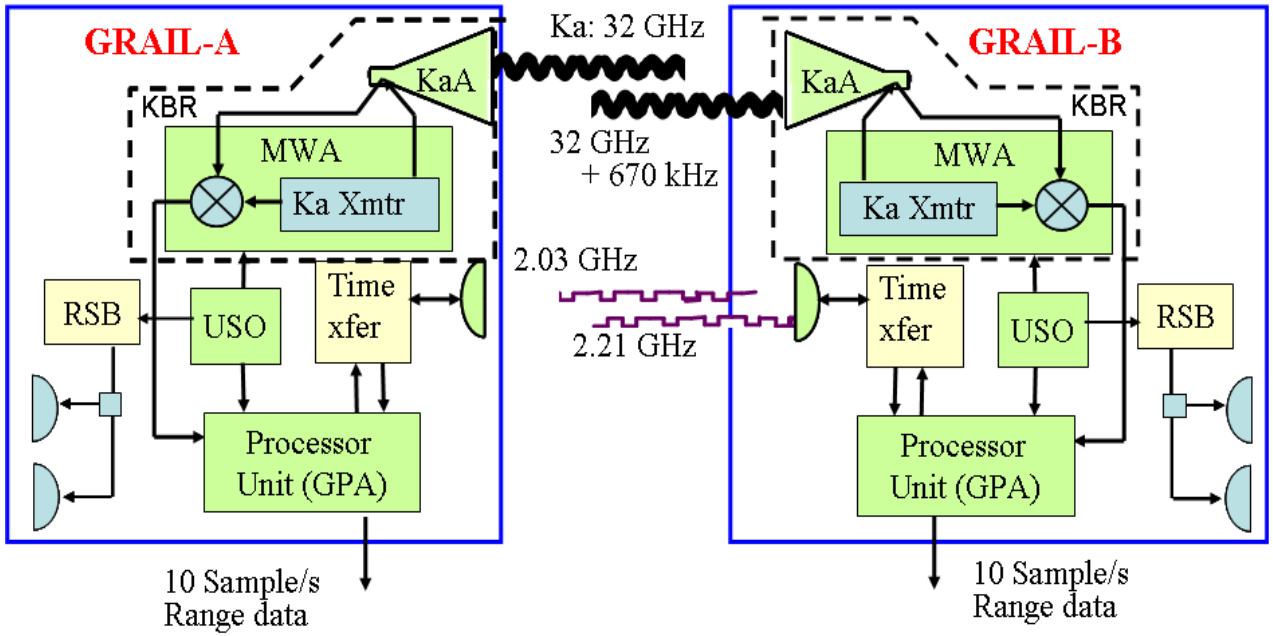
All key staff members remained on GRAIL until their tasks were completed.

GRAIL Spacecraft

- GRAIL's twin spacecraft were built by Lockheed Martin and are largely single-string
- Spacecraft based on heritage from XSS-11 (main structure and propulsion) and MRO (avionics, fight software, power)
- Launch mass of each spacecraft: 306 kg including 108 kg of fuel
- The spacecraft are 3-axis stabilized with reaction wheels and hydrazine warm-gas thrusters for attitude control, and a star tracker and an IMU for attitude determination
- A 22-N hydrazine main engine operating in blow-down mode provides thrust for all maneuvers, except the small orbit trim maneuvers that are performed with 1-N ACS thrusters
- The payload on each spacecraft consists of an LGRS and an E/PO MoonKAM with 4 camera heads

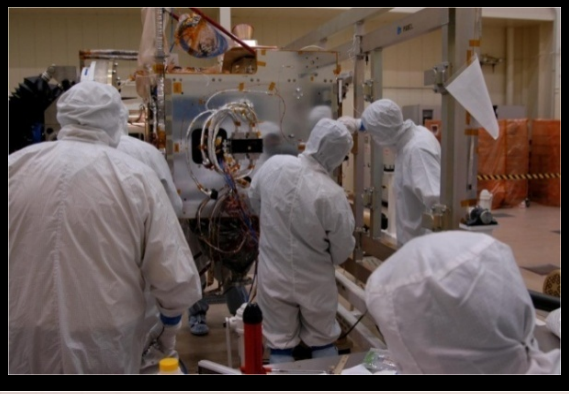
Lunar Gravity Ranging System Block Diagram

- GRAIL's Lunar Gravity Ranging System was built by JPL and 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

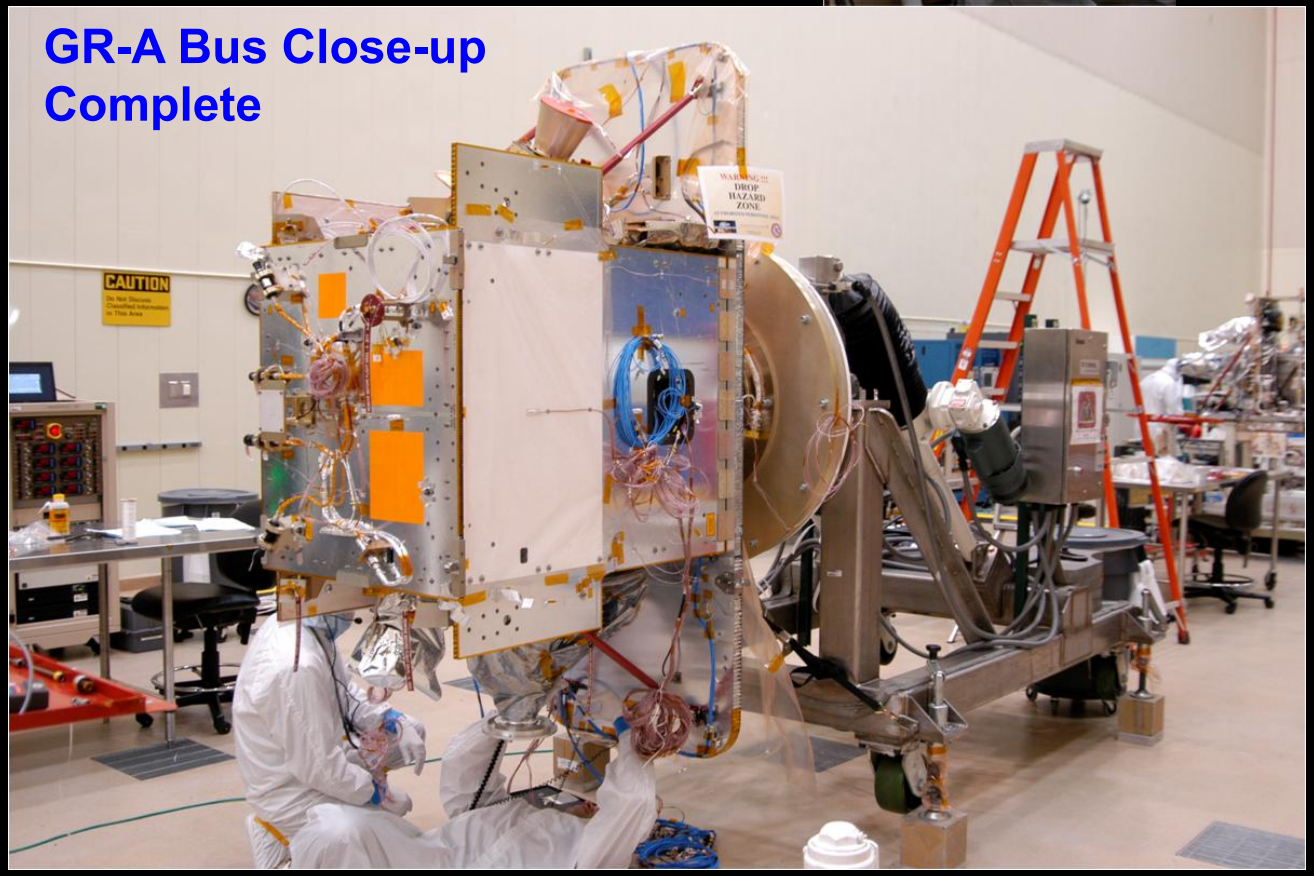


LGRS was delivered to the spacecraft 3-weeks ahead of the original plan

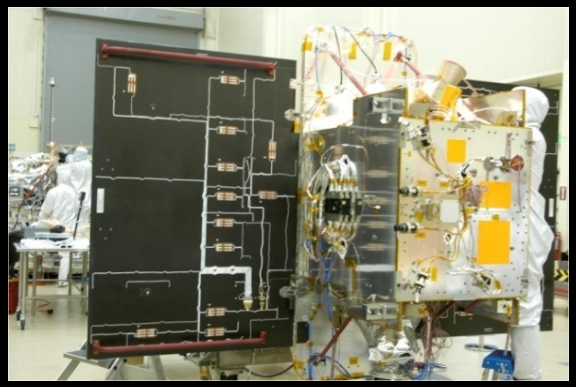
GRAIL Bus Close-up



GR-A Bus Close-up Complete



Solar Array Integration



Spacecraft Acoustic Test

Spacecraft Solar Array Test

Spacecraft Thermal-Vacuum Test

This is not the GRAIL Approach to Schedule Management

The GRAIL team worked hard to maintain the development schedule

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

NASA/MIT/JPL/GRAIL

GRAIL PI the day before launch

NASA/MIT/JPL/GRAIL

This is Mrs. Lehman and not the GRAIL Rocket

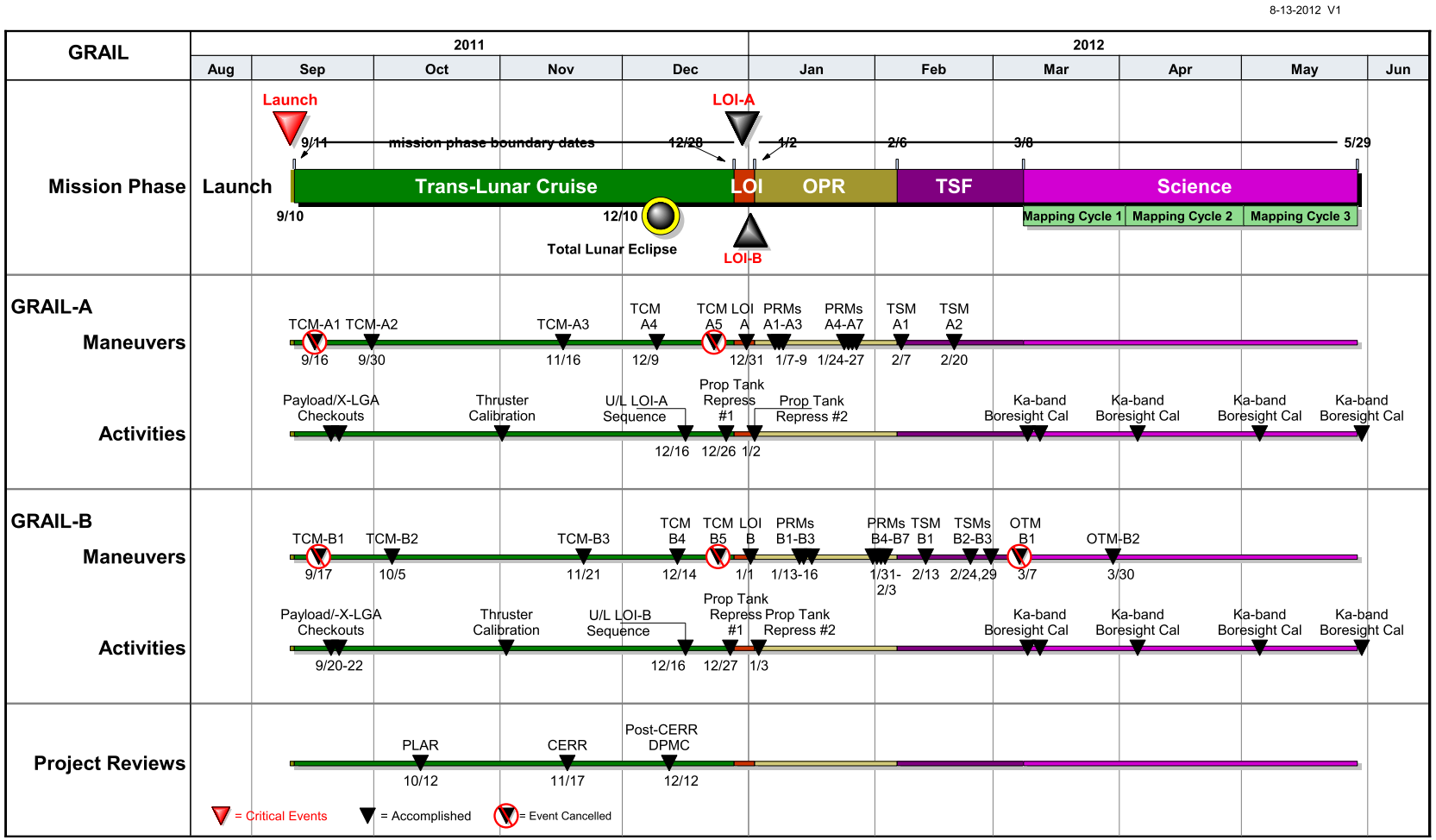
September 10, 2011 @ 9:08 am EDT
(A Great Day for the GRAIL Team!)

NASA/MIT/JPL/GRAIL

GRAIL Mission Summary

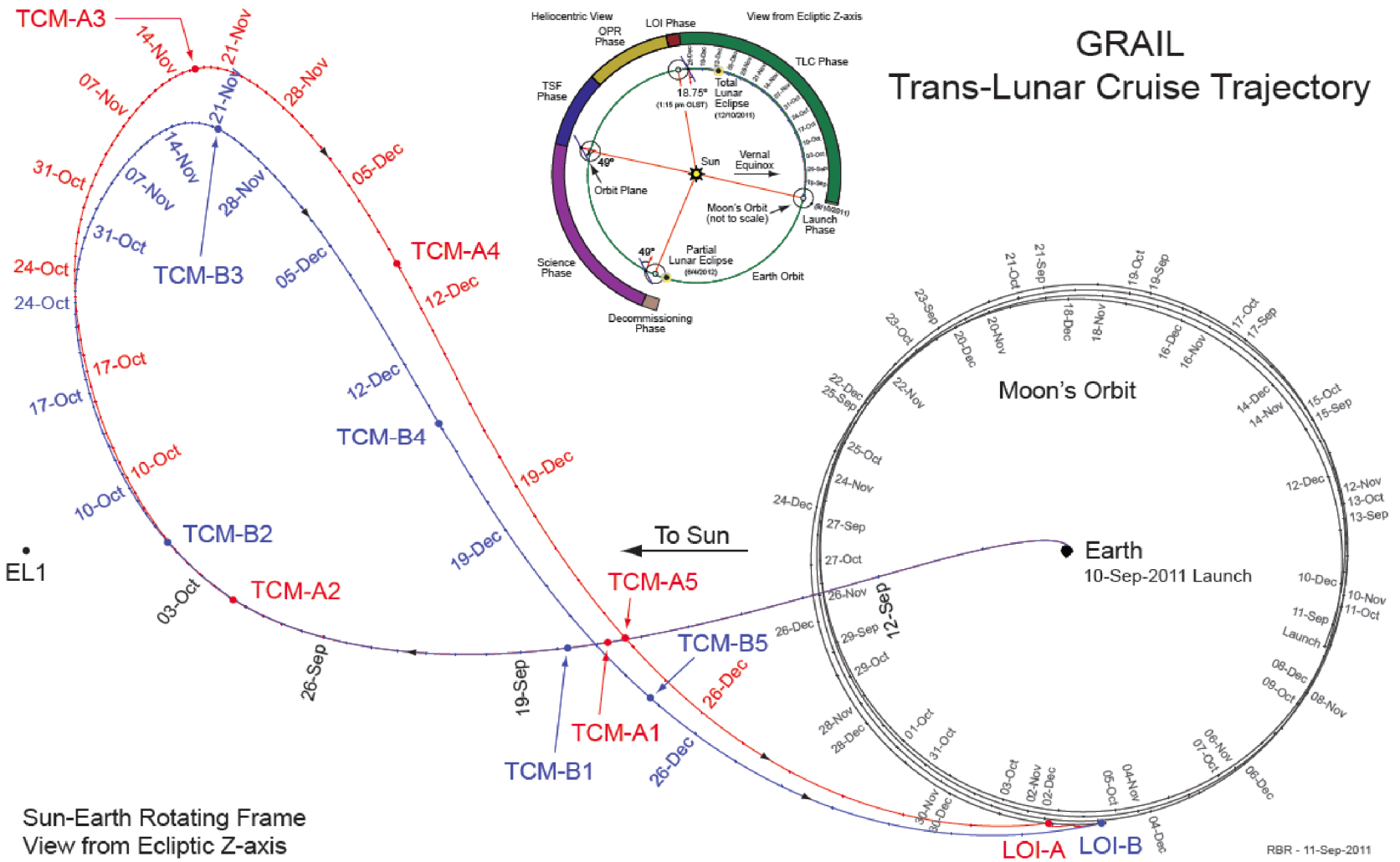
- Launch: 10 Sep 2011
- LOI (Ebb): 31 Dec 2011
- LOI (Flow): 01 Jan 2012
- PM Mission science data collection initiated: 01 Mar 2012 (1 week early)
- XM completed on 17 Dec 2013
- Days of operation: 465
- Days of science data collection: 195
- Number of lunar orbits: 4288/4205 (Ebb/Flow)
- Number of command files radiated: 1421/1383 (Ebb/Flow)
- Number of maneuvers: 78 (Ebb + Flow)
- Number of safe mode entries: 0
- >99.99% of PM and XM data acquired and returned to Earth

Prime Mission Schedule



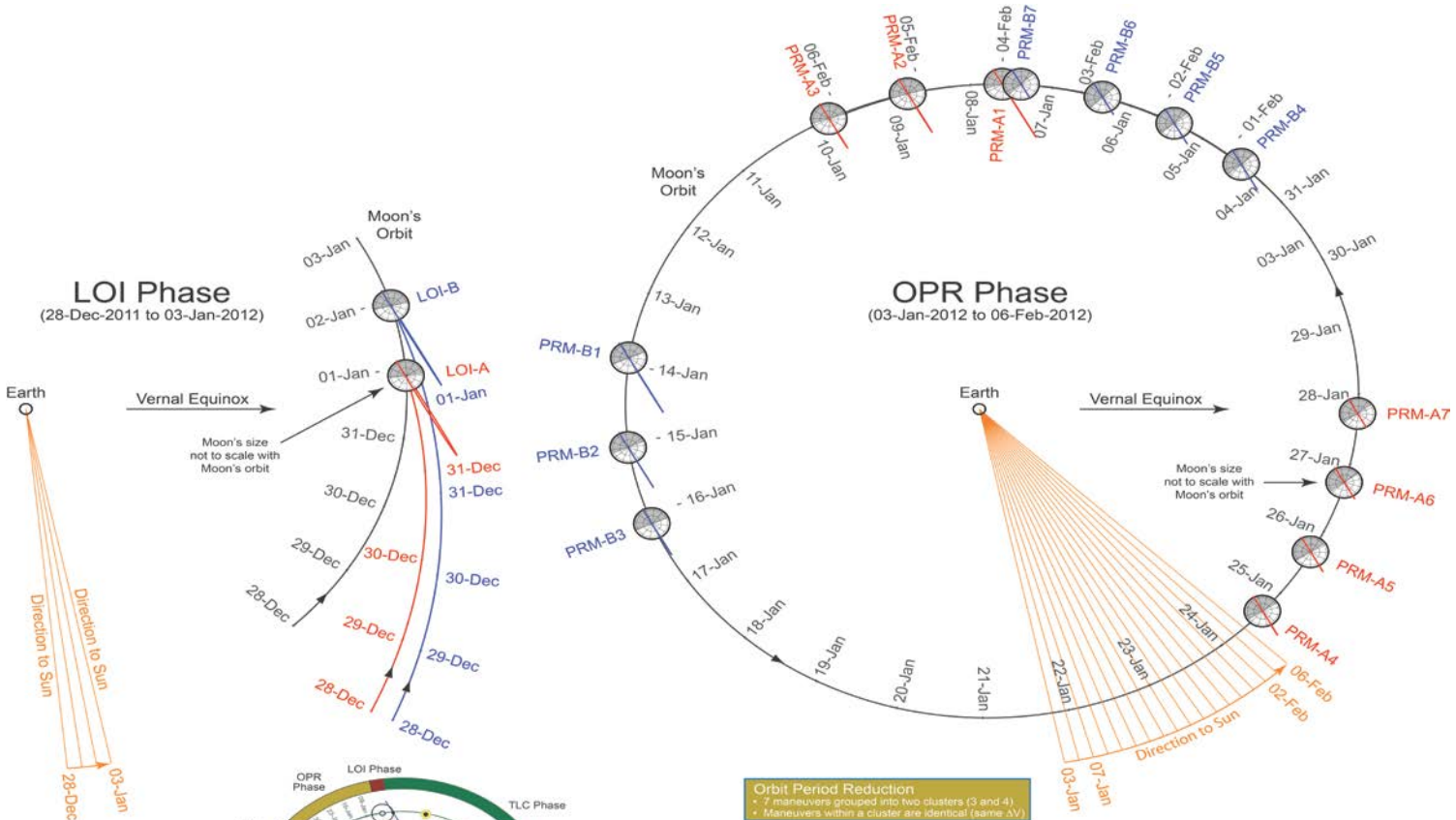
28 maneuvers performed flawlessly to reach science orbits

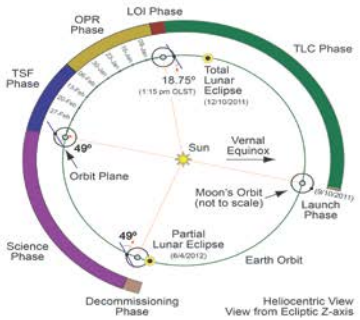
GRAIL TLC Phase

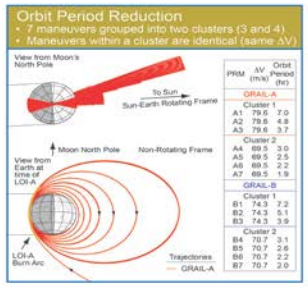


NASA/MIT/JPL/GRAIL

GRAIL LOI and OPR Phases



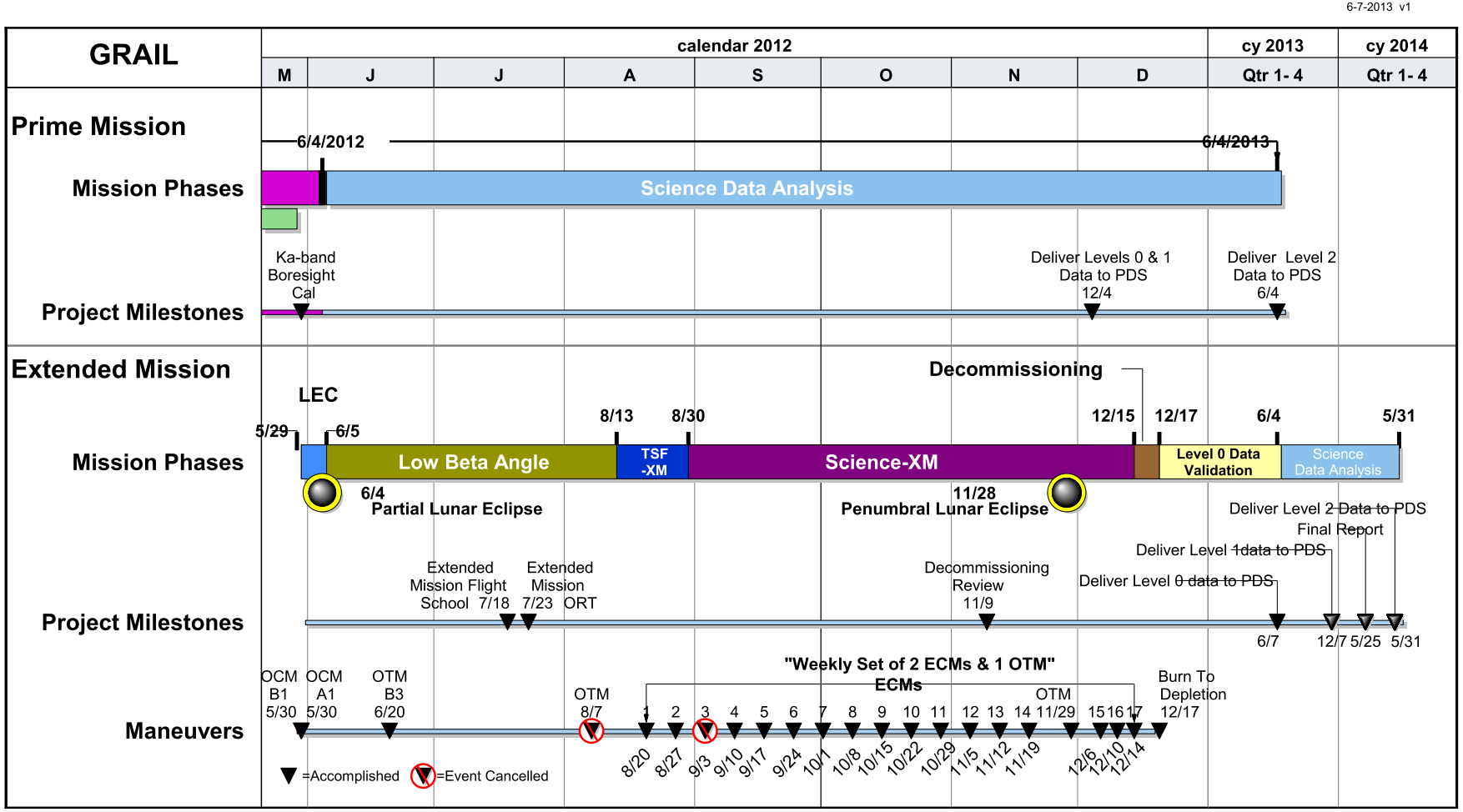




NASA Administrator Bolden Visiting the GRAIL MSA

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

Extended Mission Timeline



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

Managing GRAIL: Lessons Learned (1/2)

- Solid concept from inception
  - First-class system engineering team
  - Level-1 science requirements never changed
  - Propose what you're going to launch; launch what you proposed
  - Limited & clean interfaces, large technical resource margins, healthy cost & schedule reserves
  - Good flight and ground system inheritance with no new technology development

- Comprehensive formulation
  - Early prototyping of instrument in JPL testbed
  - A full battery of Inheritance Reviews early on, led to no liens going into Phase C

- Agile implementation
  - Aggressive identification and response to technical problems (launch loads, reaction wheels, avionics)
  - Made an opportunity out of two spacecraft
  - Resilient ATLO schedule (started on originally-proposed date, made wise use of funded schedule reserve)
  - Pushed hard on team to complete all work before launch (no deferred development)

Managing GRAIL: Lessons Learned (2/2)

- Excellent team
  - Experienced team with mature processes at JPL and LM
  - Key personnel in original proposal stayed through completion
  - Cohesive “GRAIL Team,” transparent communication, mutual aid

- Focused project management
  - Hands-on PI
  - Aggressive but doable schedule, with life-cycle reviews used as control milestones for the entire team
  - Few changes, carefully controlled (the baseline was always clear)
  - Focus on closing (e.g., trade studies in Phase A, open paper in Phase D)
  - Value-added contract surveillance, streamlined and embedded in the work activity

GRAIL team to date has achieved all development, operations and data analysis milestones on time, on spec and under budget.

Back Ups