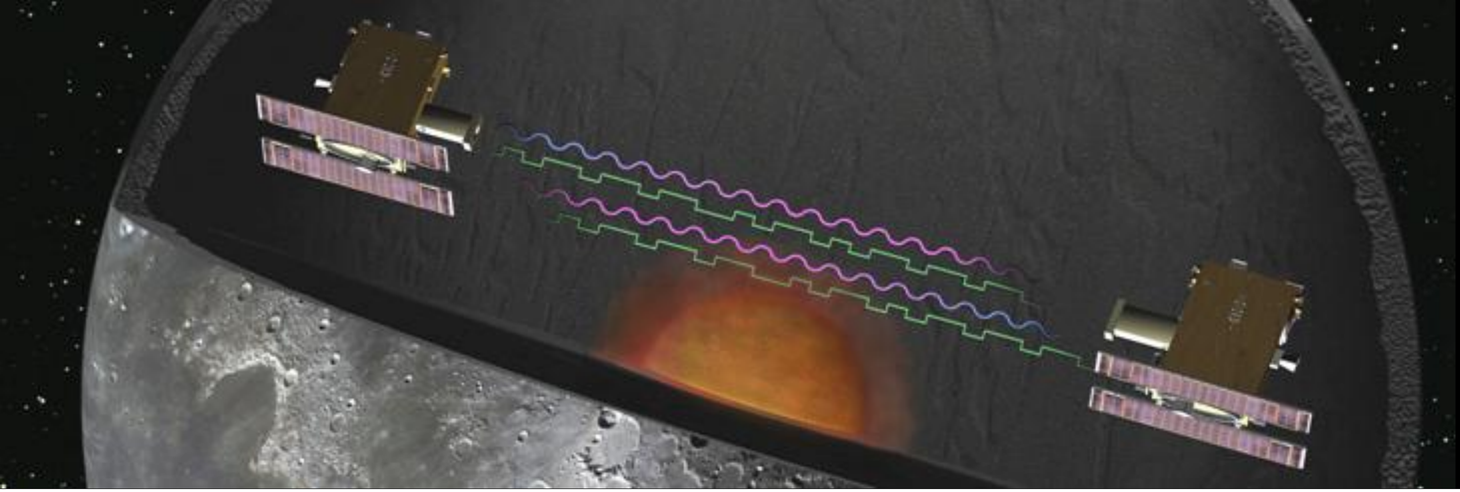


GRAIL

Gravity
Recovery
and
Interior
Laboratory

NASA GRAIL Spacecraft

Formation Flight, End of Mission Results, and Small Satellite Applications

Christine Edwards-Stewart

Lockheed Martin Space Systems Company

Introduction

- Overview of Gravity Recovery and Interior Laboratory (GRAIL) mission
- GRAIL design evolution from small-satellite technology
- Small-satellite formation-flight applications
- Lessons learned for future small-satellite missions

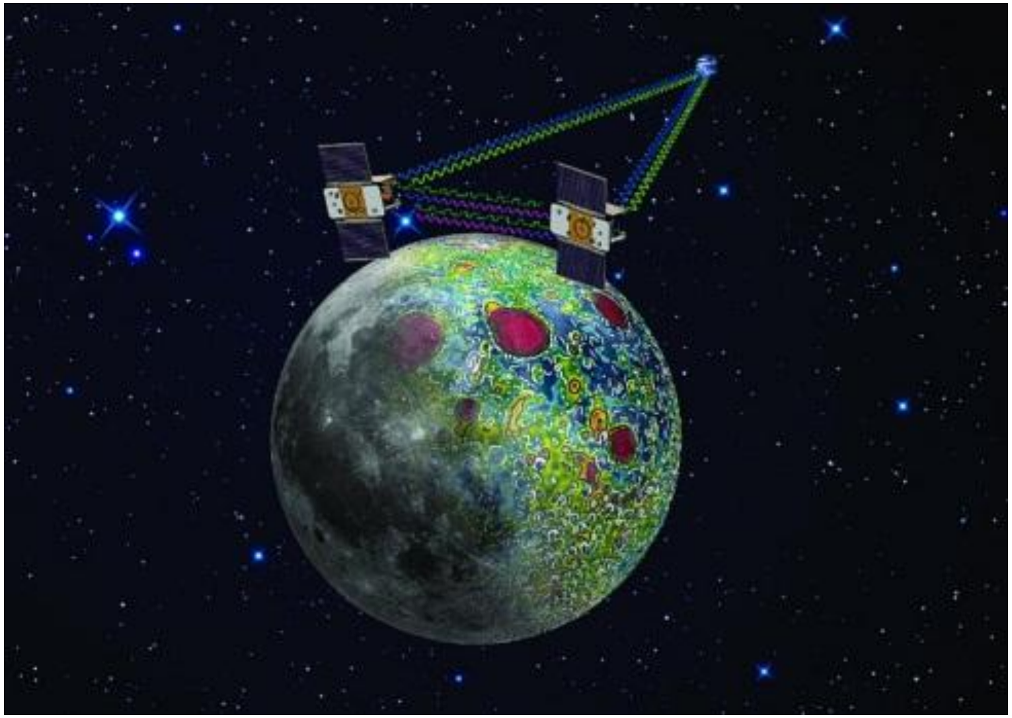
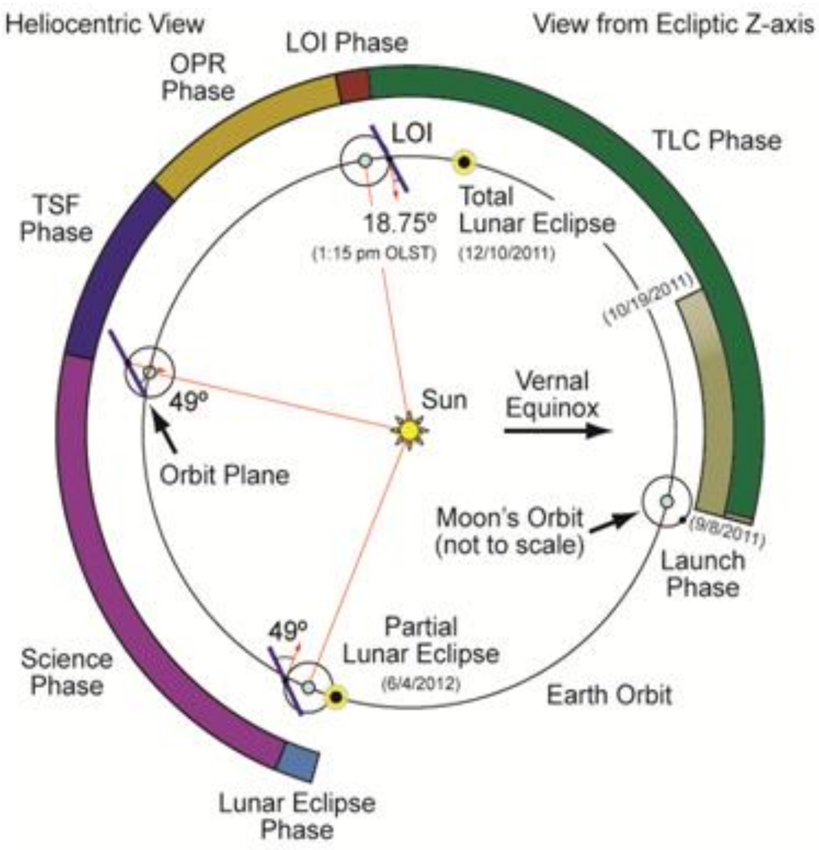


Image Courtesy NASA/JPL-Caltech

Overview of Mission

- NASA Discovery Program mission to develop high-resolution gravity map of Moon
- Team: NASA, JPL, Lockheed Martin, Goddard, MIT, and Sally Ride Science

Primary Mission
Separation of 175-225 km
Average Altitude of 55 km



Extended Mission
Separation of 40 km
Altitude as low as 11 km

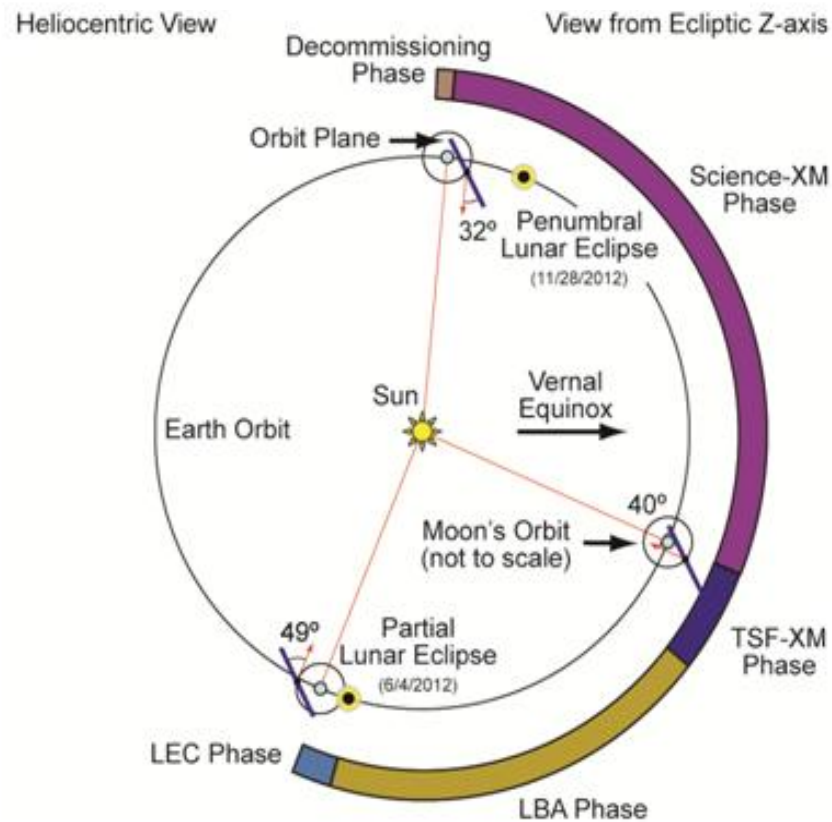
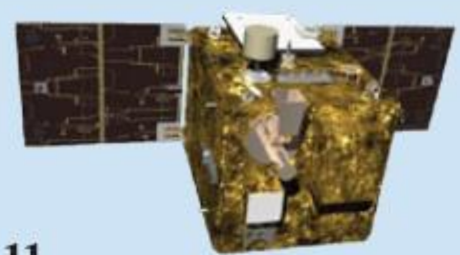


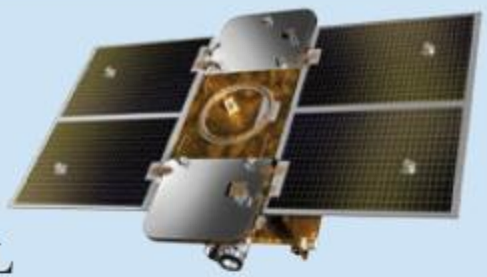
Image Courtesy NASA/JPL-Caltech

GRAIL Design Evolution from Small-Sat Technology

- GRAIL adapted from the platform of XSS-11
  - *XSS-11 was an AFRL technology demonstration mission for autonomous rendezvous and proximity operations*
  - *Implemented the LM 300 bus*
  - *Modifications made to increase propellant tank and solar array sizing to meet mission's delta-v and power requirements*



XSS-11
- Experimental Satellite System-11
- Autonomous Rendezvous & Proximity Operations for MicroSats
- Baseline for LM 300 Bus
- 100 kg
- Launched: April 2005



GRAIL
- **G**ravity **R**ecovery and **I**nterior **L**aboratory
- High Resolution Mapping of the Moon's Gravity Field
- Studying Lunar Interior Structure
- Utilizing the LM 300 Bus
- 133 kg
- Launched: Sept 2011

Formation Flight Approach

- Primary science instrument, the Lunar Gravity Ranging System (LGRS)
  - *Measured range with the K_a-band inter-spacecraft link*
  - *Each LGRS pointed towards the other spacecraft along the –Z axis in the local spacecraft body frame*

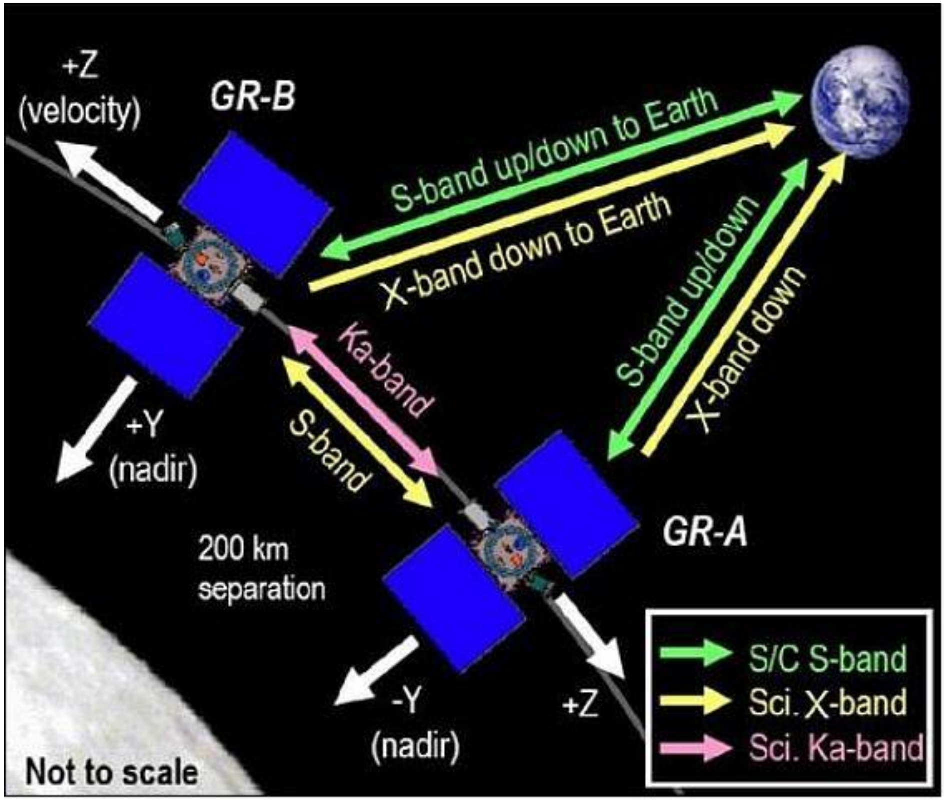


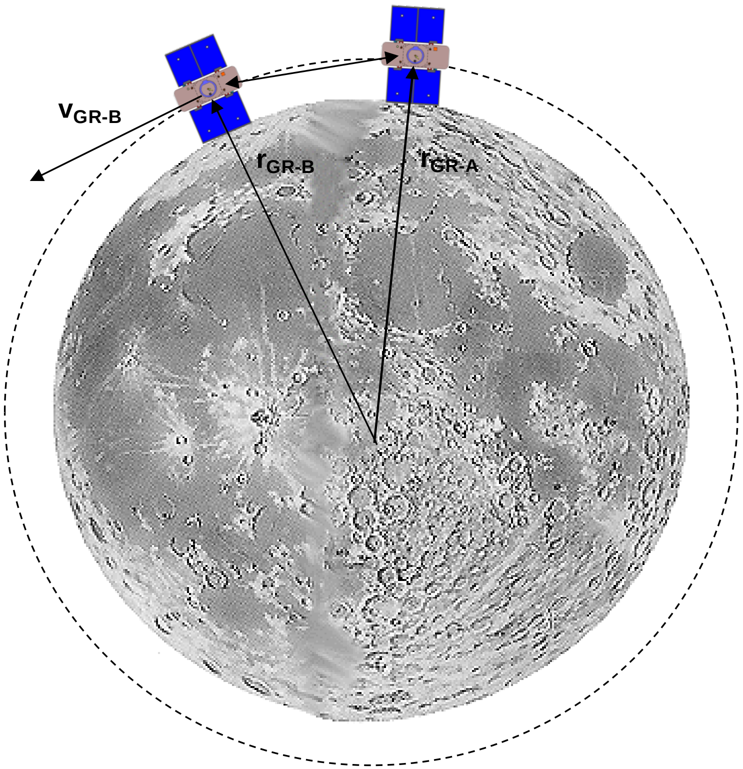
Image Courtesy NASA/JPL-Caltech

LOCKHEED MARTIN

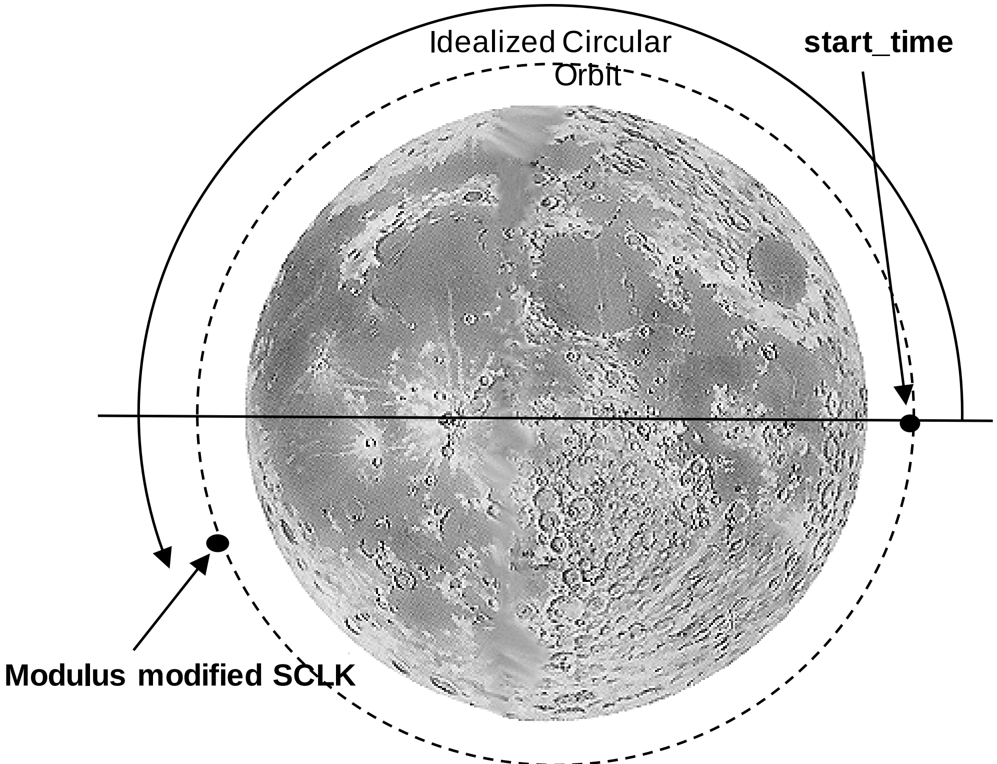
Formation Flight Approach, continued

- Dual spacecraft system's elliptical orbits represented with Chebyshev polynomial coefficients as an input to flight software, called the Ephemeris files

Orbiter Point Mode	Contingency Velocity Point
Ephemeris files formed the basis for the relative reference vectors in spacecraft-to-spacecraft pointing, or Orbiter Point Mode	Contingency implementation was a circular orbit representing the mean of the actual elliptical orbit, modulus modified SCLK, and Velocity Point



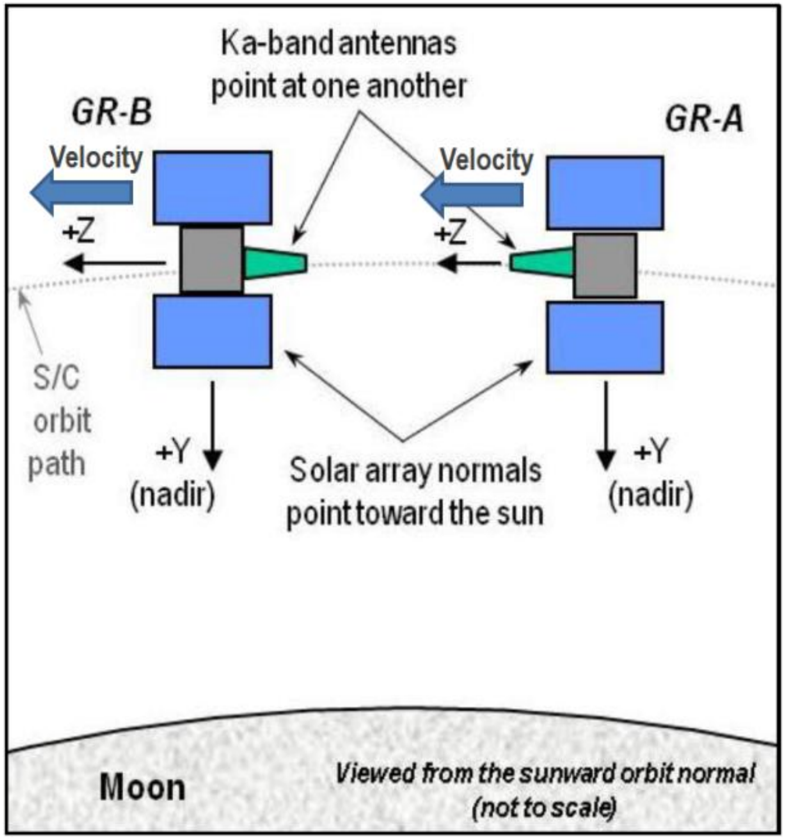
Orbiter Point Mode with Nominal Orbit



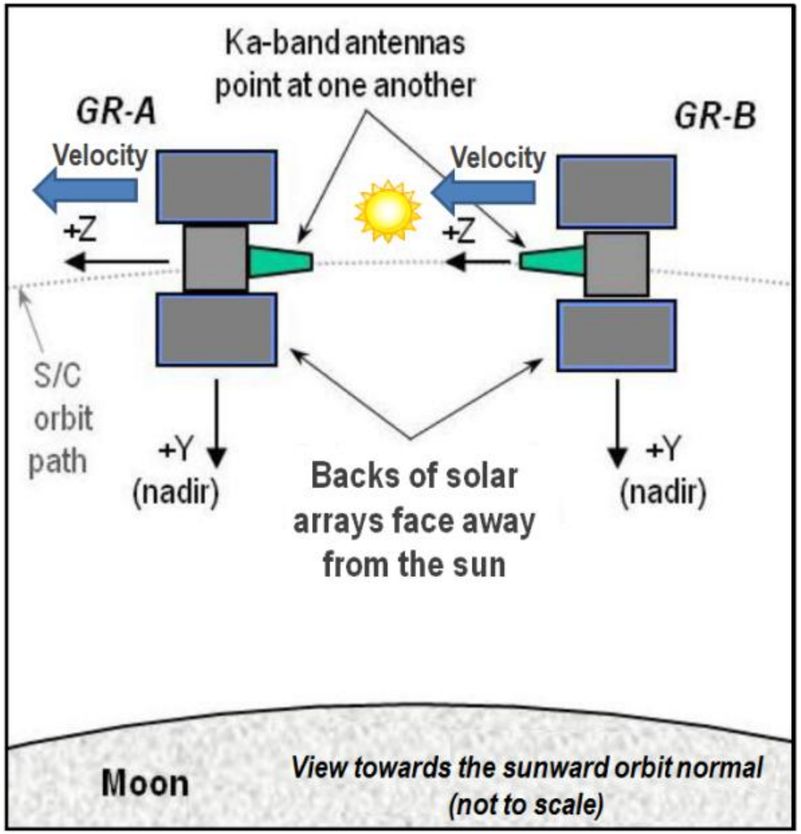
Velocity Point with Contingency Orbit

Adjusting the Formation for Extended Mission

- Geometry between Sun and spacecraft orbit changed from primary to extended mission
  - *Caused the need to swap GRAIL-A and GRAIL-B positions in the formation*



Primary Mission Science Phase

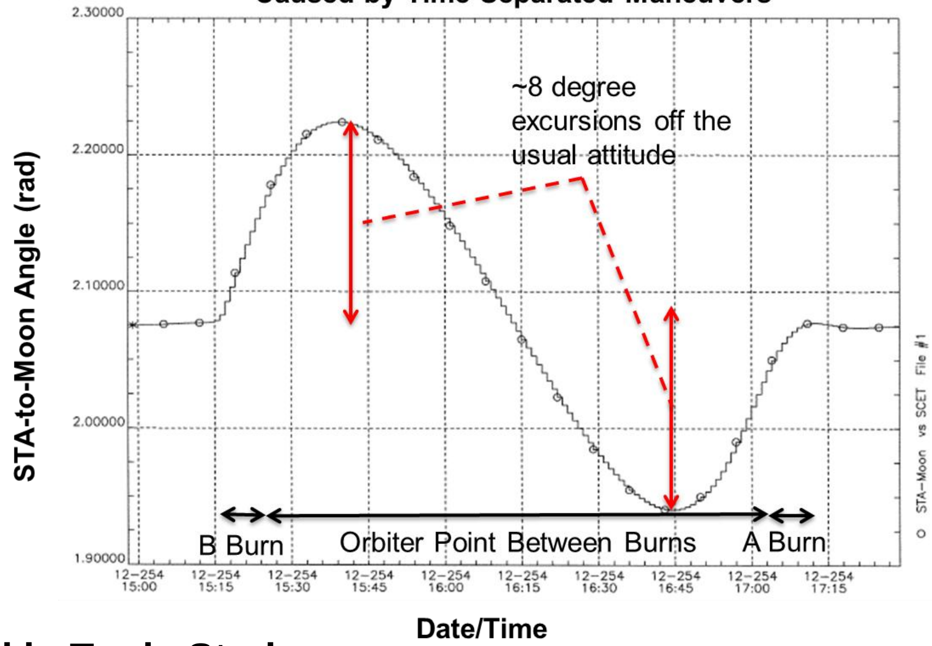


Extended Mission Science Phase

Trajectory Maintenance Maneuvers

- Frequent maneuvers were required to maintain low altitude in extended mission.
- If Orbiter Point was continued between maneuvers with a 2 hour separation, spacecraft would have significant attitude excursions.
- Trade study goals:
  - Minimize attitude excursions and operational complexity
  - Maximize science collection

Simulation Results for GRAIL-B Attitude Excursions Caused by Time-Separated Maneuvers



Options Considered in Trade Study

Option #	Option Description
Option 1	Do Nothing: Perform maneuvers with same timing separation as Primary Mission, and accept attitude excursions
Option 2	Perform maneuvers at the same time, potentially avoiding attitude excursions
Option 3	Make each spacecraft point as if the other spacecraft is still in the same orbit
Option 4	Command the spacecraft out of Orbiter Point around the maneuvers

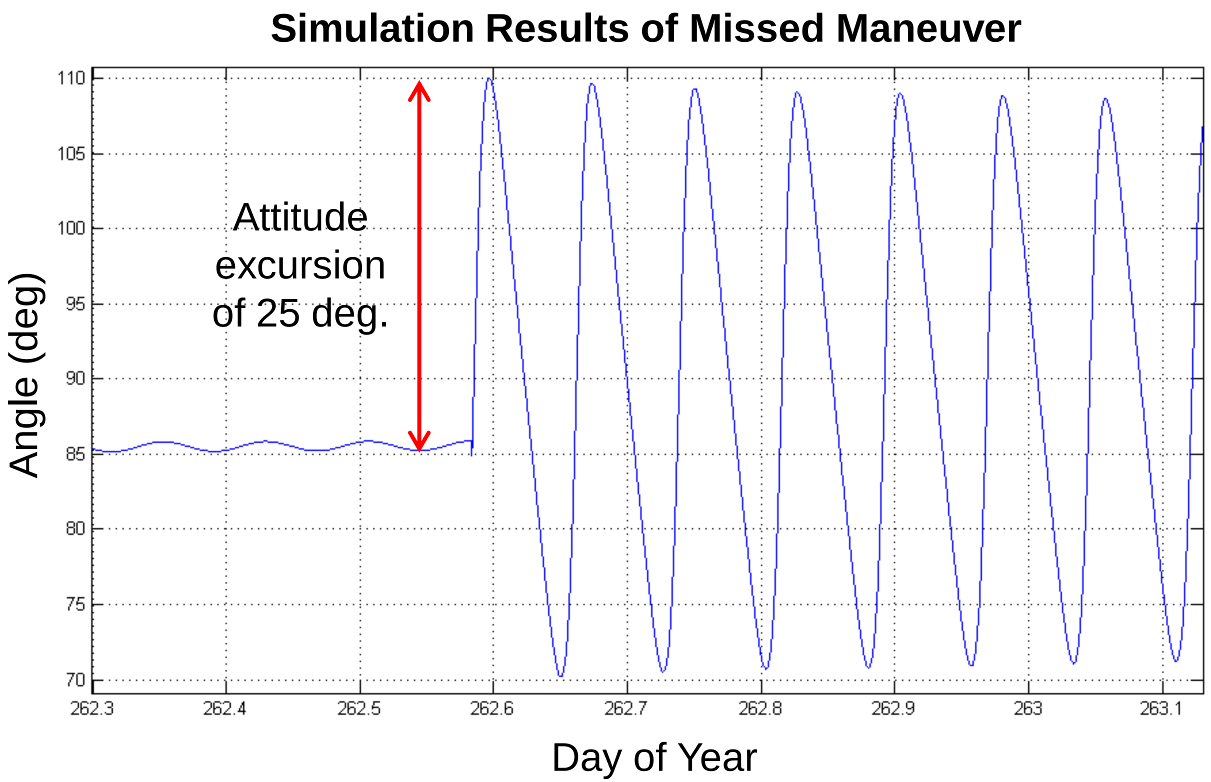
Trade Study for Formation Flight Around Maneuvers

- Best solution from trade study was to perform maneuvers nearly simultaneously

Option	Meet Attitude Error Requirements?	Operations Impact	Science Impact
Option 0: Do nothing	No	Low	Low to Medium
Option 1: Perform Burns at the Same Time	Yes	Low to Medium	Low
Option 2: Make Spacecraft Point as if Other is Still in Same Orbit	Yes	High	Medium
Option 3: Take Spacecraft Out of Orbiter Point Around Burns	Yes	High	Medium to High

Contingency Operations for Missed Maneuver

- If one spacecraft missed a maneuver, as soon as onboard ephemeris knowledge was updated, it would point at the other spacecraft in a different orbit causing attitude excursions of ~25 degrees.
- Solution: Command both spacecraft into velocity point until the next maneuver transitioned them into the same orbit again.



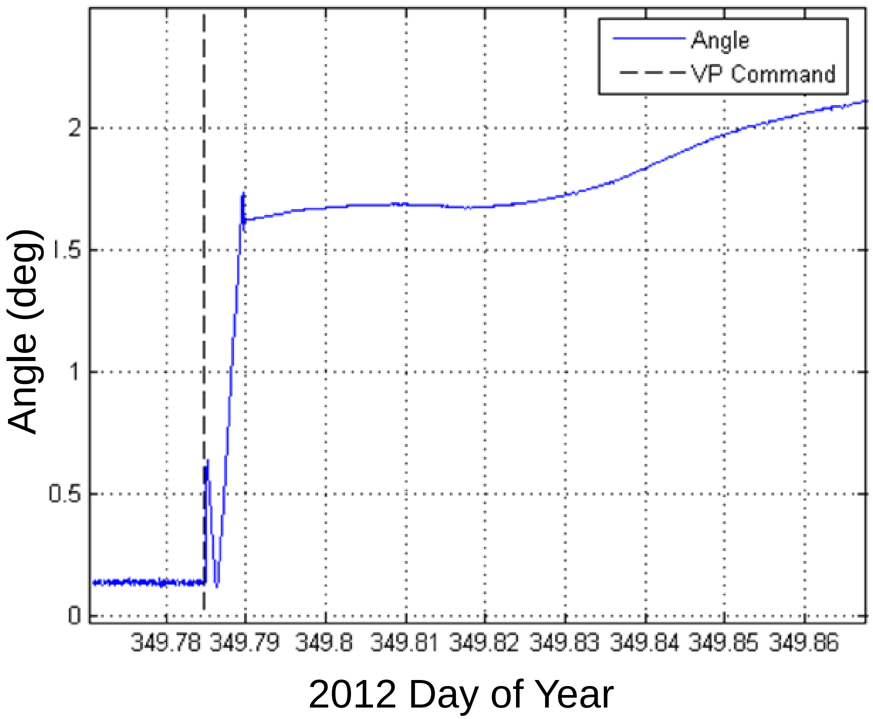
Lessons Learned

- Future small-satellites missions that can benefit from the demonstrated technology on GRAIL
  - *Formation-flight missions implementing swarm operations, distributed and networked satellites, interferometry, or gravity mapping*
  - *Future Great Observatories*
- Reuse of heritage spacecraft architecture and low-cost solutions
  - *Design costs reduced through:*
    - Reuse of XSS-11 bus
    - Implementation of innovative approach to single-string redundancy
- Formation-flight operations require vigilance to maintain situational awareness
  - *Small satellites can affect each other in formation flight*
- Preparations for changes in the formation configuration
  - *Perform careful planning, thorough investigations, stakeholder inclusive trade studies, and early simulation testing*
- Implementation of a contingency mode in case the formation is broken
  - *Velocity point mode would have enabled continued flight without dependency on other spacecraft if it had been needed*

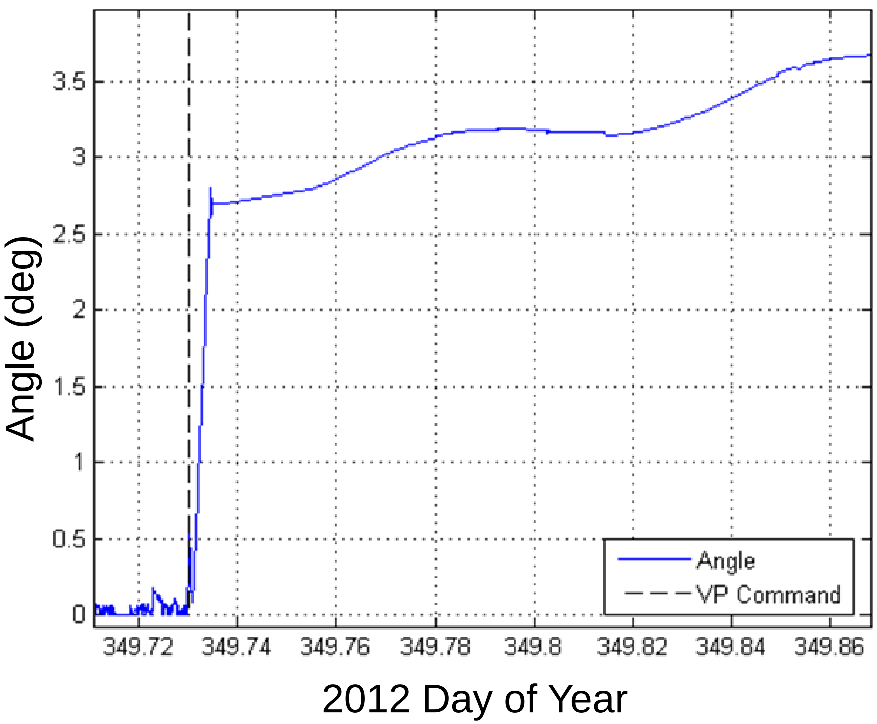
Lessons Learned, continued

- Flight demonstration of velocity point
  - *Part of decommissioning activities*
  - *Both spacecraft were commanded to velocity point as an engineering test to validate the function for future missions*
  - *Velocity point performed successfully*

Flight Results of GRAIL-A Velocity Point



Flight Results of GRAIL-B Velocity Point



Conclusion

- To obtain lunar gravity data, the two GRAIL spacecraft flew in formation with coordinated high precision pointing in an Orbiter Point Mode
- Orbital altitude of spacecraft lowered during second half of 2012 to increase the resolution of the gravity data
  - *Changes to operations made to achieve and maintain formation flight at the lower altitudes*
- GRAIL mission completed at the end of 2012
- The two spacecraft had no emergency safe mode entries, and no need to implement the contingency plans for a missed maneuver
  - *Contingency Velocity Point demonstrated during decommissioning*
- Successful mission created a lunar gravity map of unprecedented resolution