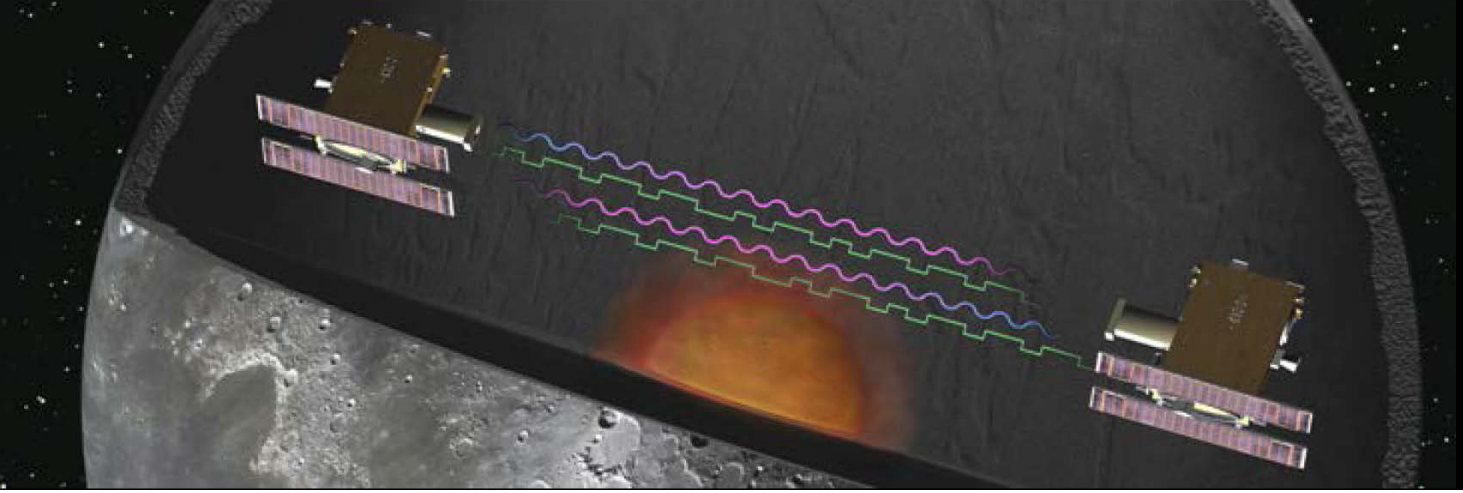

GRAIL

Gravity Recovery and Interior Laboratory

GRAIL Orbit Determination for the Science Phase and Extended Mission

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Jet Propulsion Laboratory,
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AAS/AIAA Space Flight Mechanics Meeting
Kauai, Hawaii,
10 – 14 February 2013

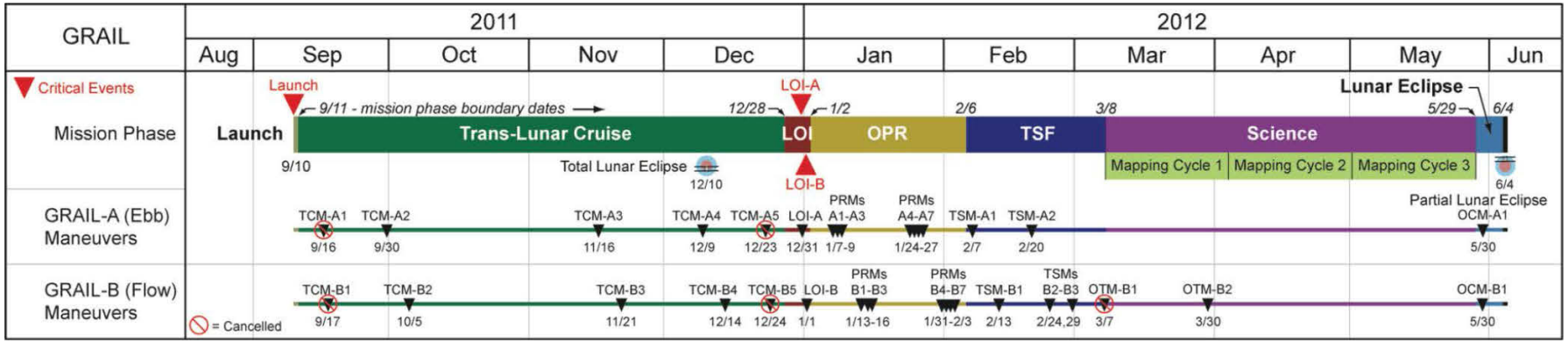
This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California under contract to the National Aeronautics and Space Administration.

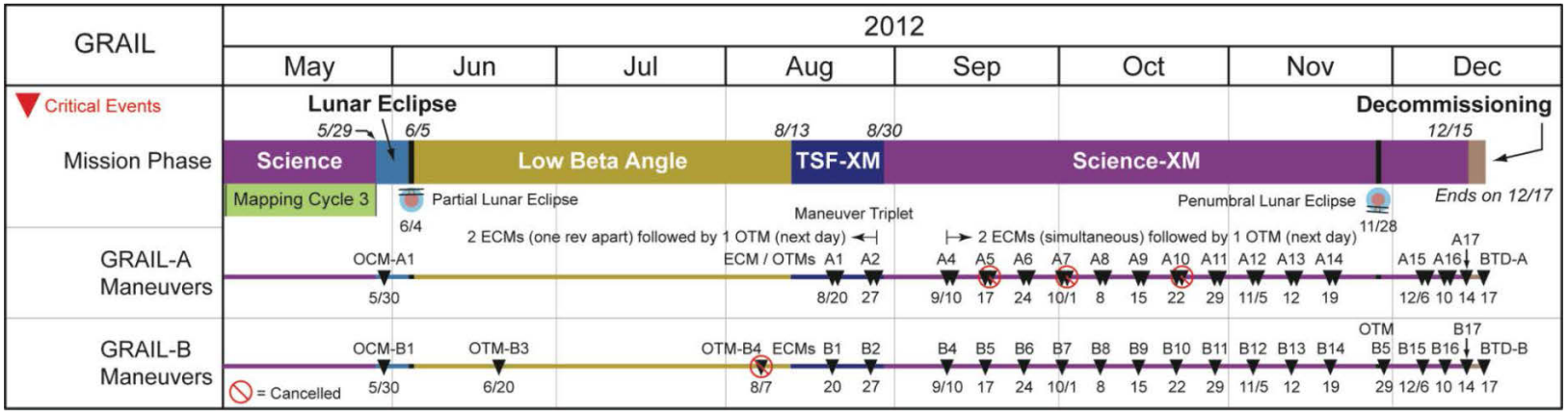
Introduction

- Gravity Recovery and Interior Laboratory Mission (GRAIL)
- 11th mission of the NASA Discovery Program
- Objective - help answer fundamental questions about the Moon's internal structure, thermal evolution, and collisional history
- Generate substantially improved global lunar gravity model, from which the above results are derived

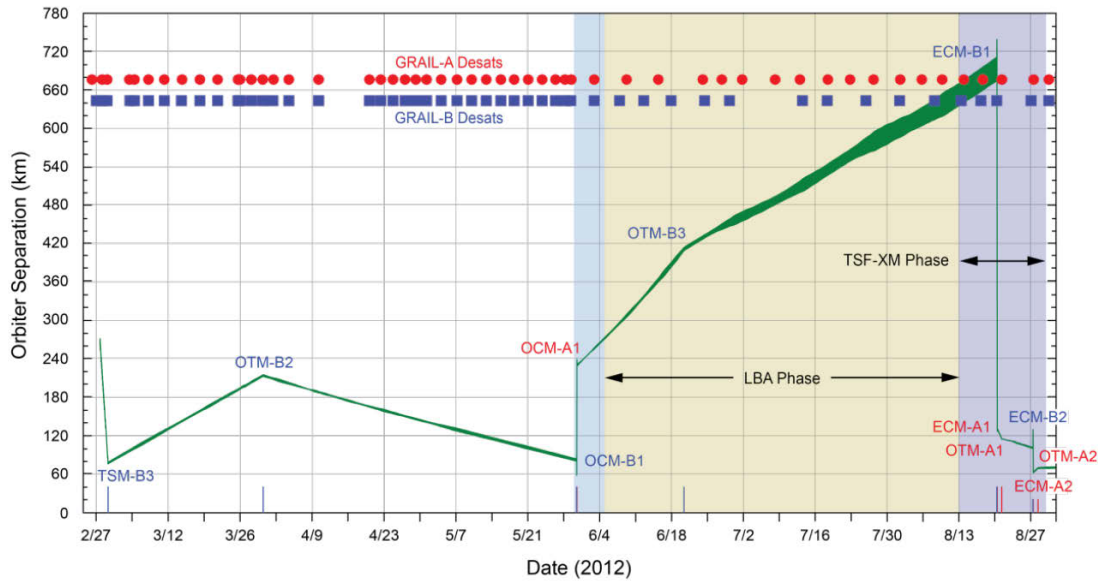
- Twin spacecraft flown in precision formation in near-coplanar, low altitude, polar orbit
- Primary science instrument: Lunar Gravity Ranging System (LGRS)
  - Collects near continuous spacecraft-to-spacecraft range-rate data
- Secondary payload: MoonKAM
  - Education and public outreach imaging system
  - Participation by middle school students and teachers
- GRAIL-A and GRAIL-B also known as Ebb and Flow

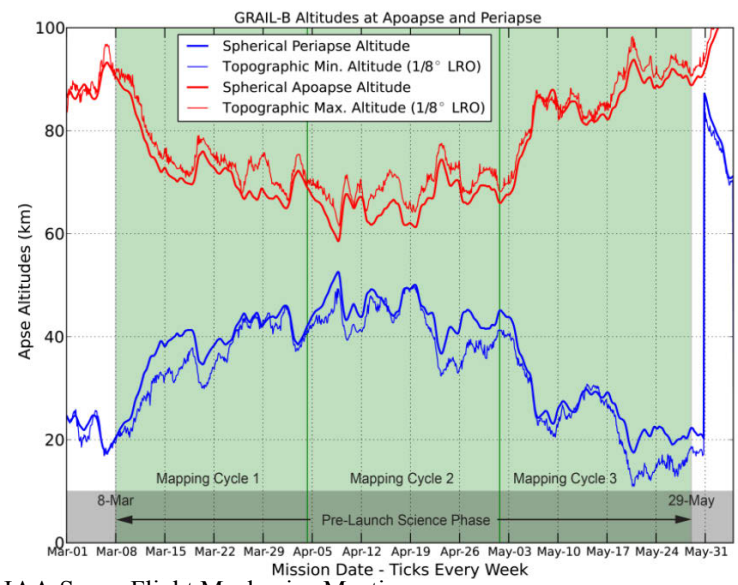
Mission Overview - 1

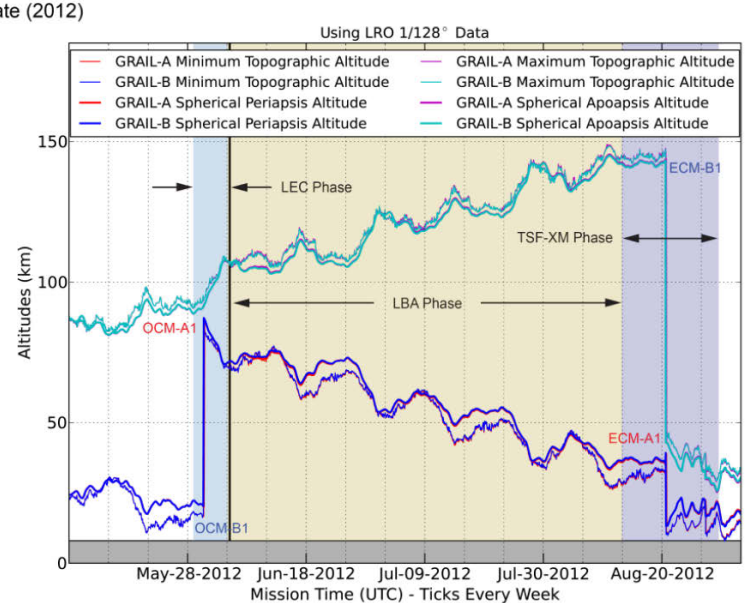




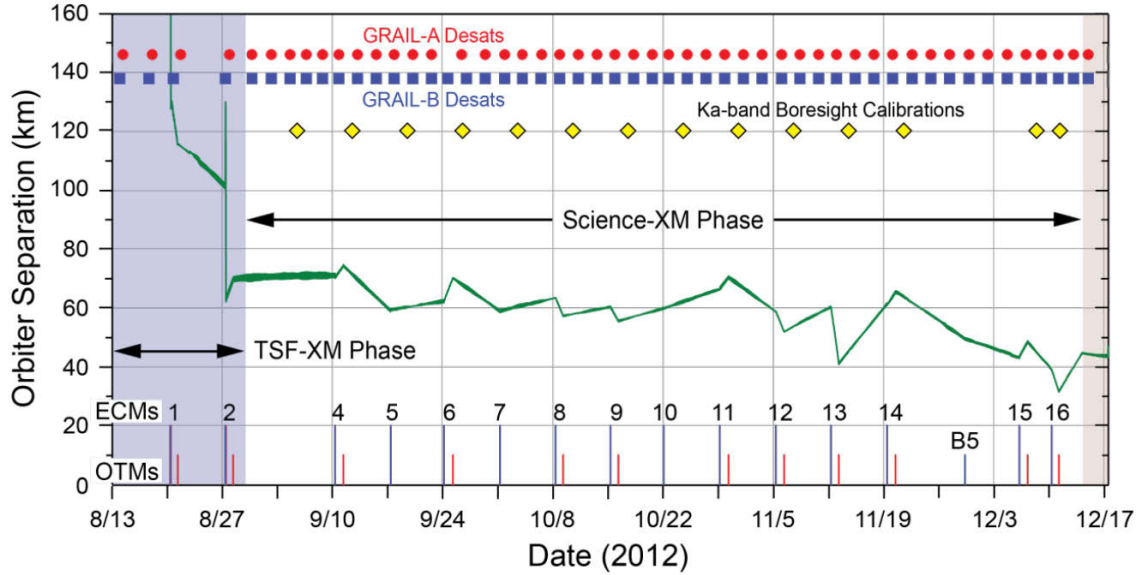
Mission Overview - 2

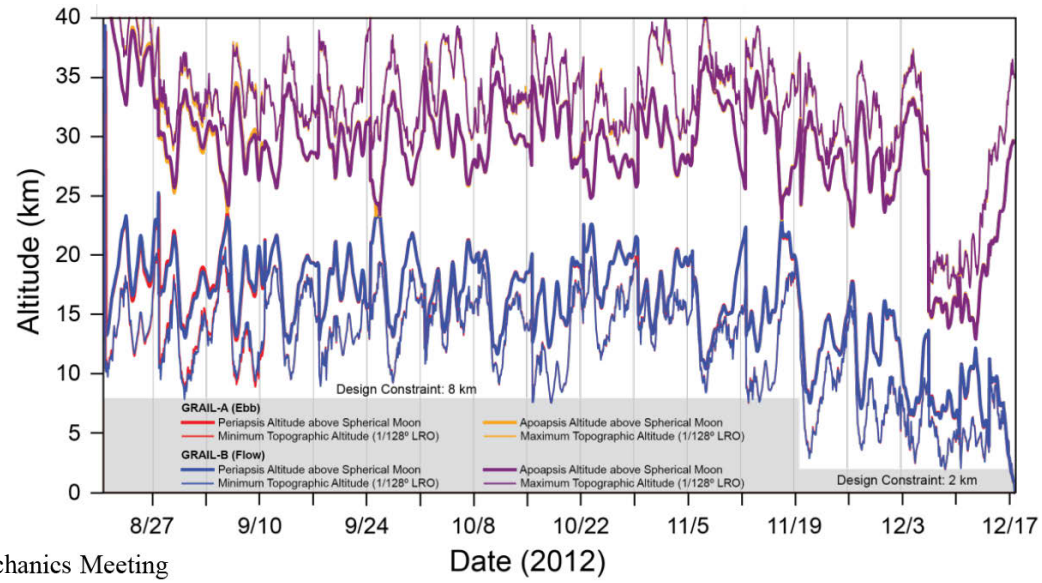






Mission Overview - 3





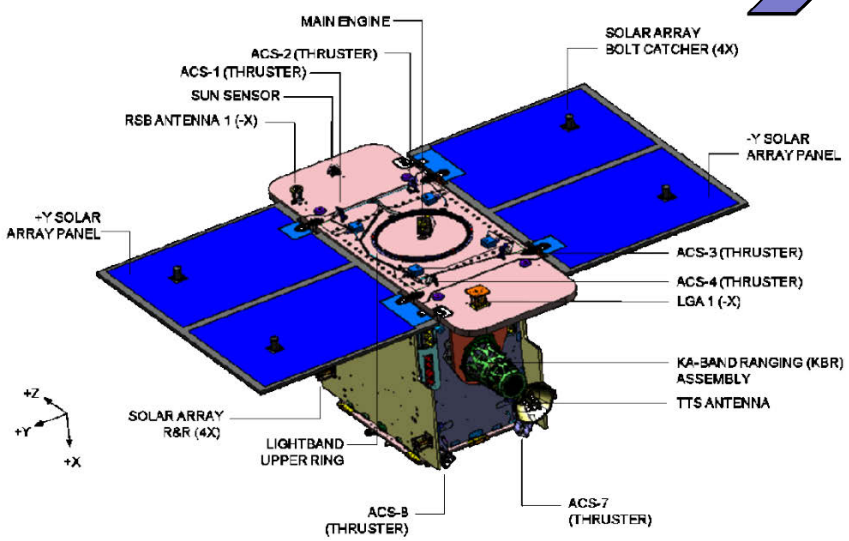
Navigation Requirements & Challenges

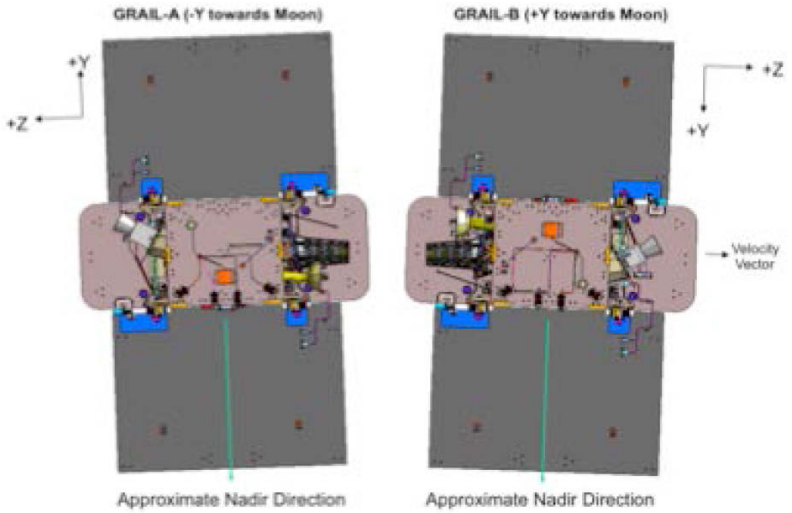
- General Navigation Requirements
  - Satisfy stringent formation requirements
    - Match orbit plane to ±0.1 degrees
    - Spacecraft-to-spacecraft pointing to ±0.073 degrees
  - Maintain spacecraft separation consistent with mission plan
  - Occultation event prediction
  - Support maneuver design and implementation

- Specific Orbit Determination Requirements
  - Orbit determination and trajectory prediction accuracy sufficient to meet above requirements despite known, significant errors in lunar gravity model
    - Period knowledge within the fit: 0.005 seconds
  - Orbit determination process optimized to meet timelines needed for mission planning, maneuver design & monitoring, sequence implementation and predicts generation & validation
  - Note: no requirement on trajectory reconstruction

Spacecraft Description

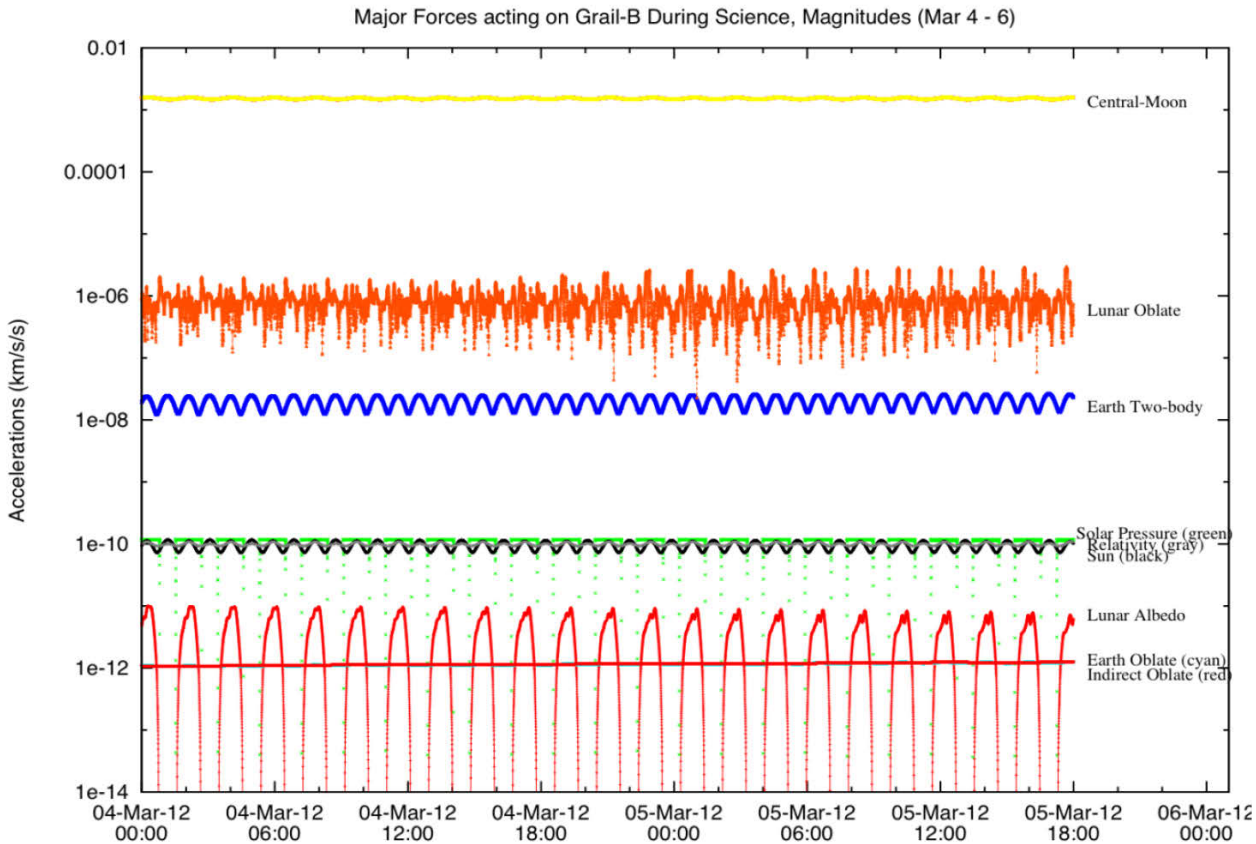
- Identical hardware for both spacecraft
  - Only LGRS and star tracker mounting are different
- Wide solar panels to shade science instruments and star tracker
- 22 N main engine (ME)
- Eight 0.9 N Attitude Control Thrusters (ACS)
- Three-axis stabilized with reaction wheels
- S-band and X-band telecomm
- LGRS includes Ka-band ranging system and USO
- Mass at start of SCI: ~306 kg
  - ~20 kg propellant





Spacecraft Dynamics

- Forces include: Central body gravity, Earth & Moon oblateness, solar pressure, lunar albedo, Earth two-body acceleration, and propulsive events
- Lunar oblateness is the dominant error source in low lunar orbit



Gravity Modeling

- Initial gravity model – LP150Q spherical harmonic field
  - Derived from ground based S-band Doppler tracking
  - No direct measure of far side gravity accelerations
- Subsequent models – internally available engineering models
  - Based on GRAIL LGRS Ka-band spacecraft-to-spacecraft range data
  - Global coverage
  - Various degree and order expansions and truncations

Date of First Use	Field ID	Truncation	Phase	Solution ID	Lockfile
March 7, 2012	lp150q	150x150	SCI	od118	4.4
April 13, 2012	grail270a9a	200x200	SCI, LEC, LBA	od156	5.0
June 7, 2012	grail360b6a	200x200	LBA	od211	6.1
August 3, 2012	grail420c1a	200x200	LBA, TSF-X, SCI-X	od249	7.1
September 1, 2012	grail420c1a	300x300	SCI-X	od276	7.2
October 26, 2012	grail540c3a	320x320	SCI-X	od320	8.1
December 6, 2012	grail660c5a	400x400	SCI-X, DEC	od355	9.2

Propulsive Events

- Main engine maneuvers
  - Orbit Correction Maneuvers (OCM) and Eccentricity Correction Maneuvers (ECM)
    - 4.5 – 15.0 m/s
    - Turn and burn
    - Blowdown system: thrust ~50% of peak a beginning of SCI phase
  - Burn to Depletion (BTD)
    - Special main engine burn to validate propellant consumption models
    - 15 – 55 m/sec

- ACS system maneuvers
  - Orbit Trim Maneuvers (OTM)
    - 20 – 90 mm/sec
    - Pitchover to remain in orbiter-to-orbiter point and maintain LGRS link
  - Momentum wheel desaturations
    - Coupled ACS thrusters
    - Less than 0.2 mm/sec
    - One event every 2 – 4 days

Tracking Data

- S-Band for two-way Doppler, commanding and spacecraft telemetry
- X-Band for one-way Doppler, payload timing uplink and science data return
- Limited DSN assets support both frequency requirements
  - 6 stations capable of S-band
    - Only 5 of these stations capable of supporting both S-band and X-band
  - 7 station capable of supporting X-band
- DSN tracking request: one tracking pass per day per orbiter with no gaps longer than 16 hours
  - Primarily satisfied using 34m stations
  - Tracking request not always satisfied during SCI-XM due to conflicts with other projects – especially when GRAIL and Mars in save view
  - Failure of 34m station in Madrid led to the use of Multiple Spacecraft Same Aperture (MSPA) technique used near end of mission

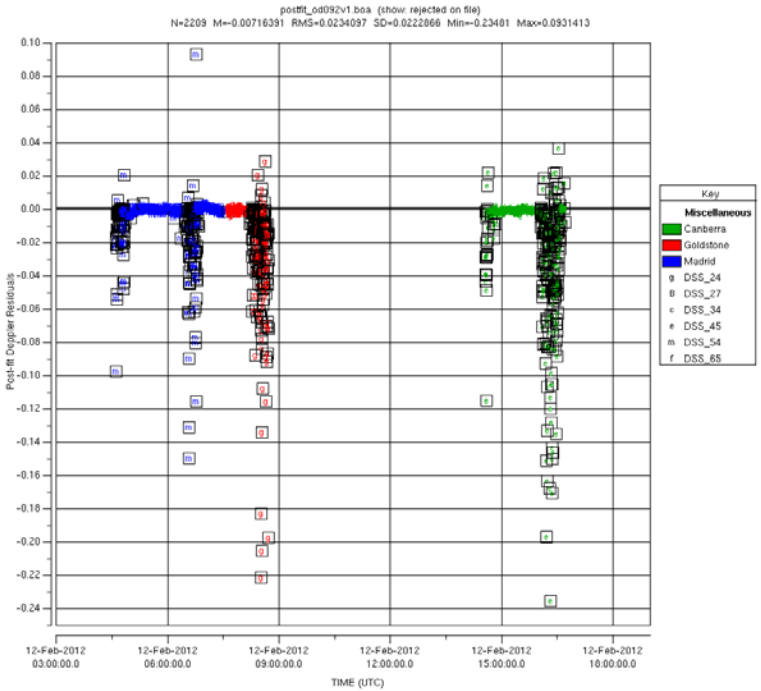
Orbit Determination Filter Setup

- Goal: orbit determination strategy must be robust in presence of large, expected gravity mismodeling
- On-orbit experience demonstrated that solving for local gravity field or accelerations resulted in a poor trajectory prediction
- Simple orbit determination filter
  - Solve for state, solar radiation pressure scale factor
  - Finite maneuvers for ME & ACS burns and impulsive maneuvers for momentum wheel desaturations
  - SCI, LEC and LBA phase only: per-periapsis impulsive burns
    - Account for gravity mismodeling
  - Stochastic models for media and future gravity error
  - Consider Earth/Moon GM and ephemeris, station locations, pole location and UT1
- Data strategy
  - Deweight Doppler data to reduce effect of gravity mismodeling
  - Per pass weighting

Operational Issues

- Beginning of integration and end of data arc close to apoapsis
- Data arc 16-24 hours for edge-on or skewed orbit geometry
- Data arc 30-36 hours for face-on orbit geometry
- Advance data arc 24 each day with 2-4 orbits of overlap
- Keep maneuvers and desats near center of data arc
- Delete 20-40 minutes of data centered at periapsis as needed
- Remove data corrupted by multi-path

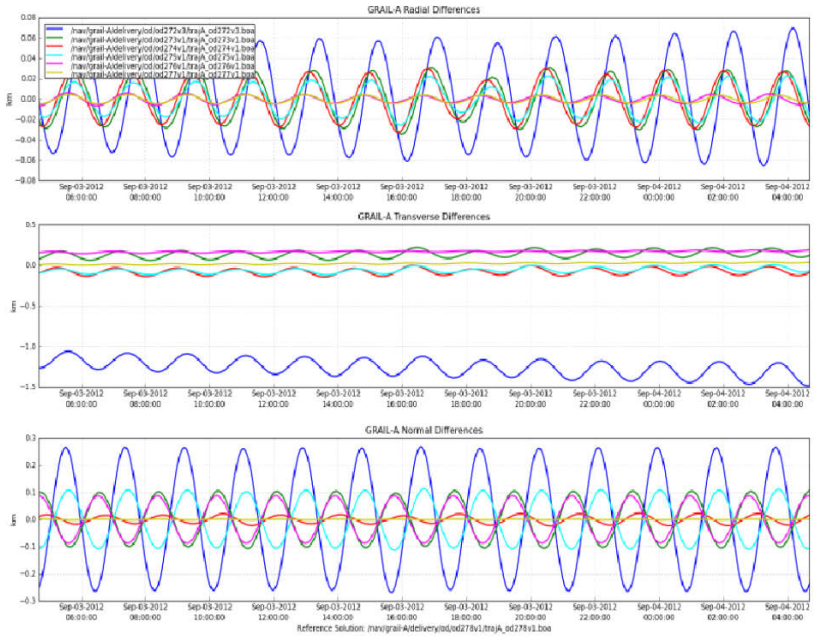
Example of Multi-Path Corruption of Doppler Tracking Data



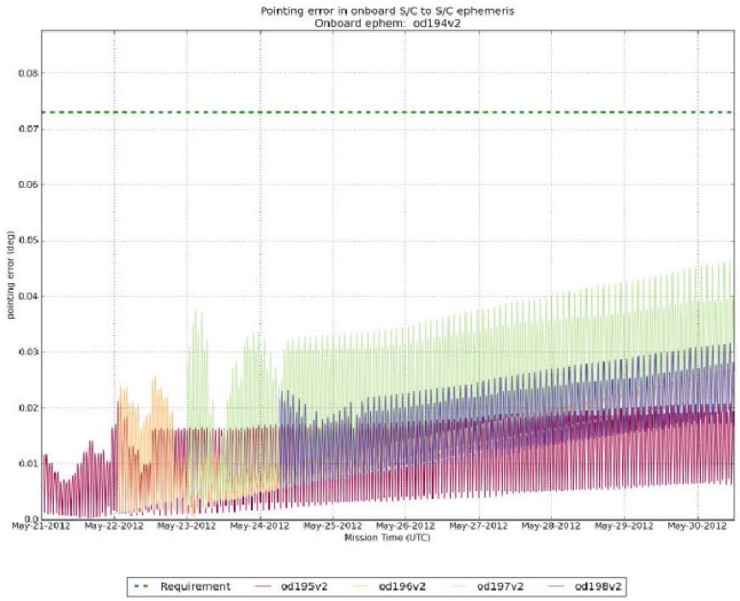
Orbit Determination Scenario

- Daily orbit determination
- Twice weekly delivery of solutions to project and DSN
- Monitor solution overlap error, long term trends in orbital elements, spacecraft-to-spacecraft pointing, occultation entry/exit time prediction

Predicted Trajectory Comparison



Spacecraft-to-Spacecraft Pointing



Orbit Determination Activities in SCI-XM Phase

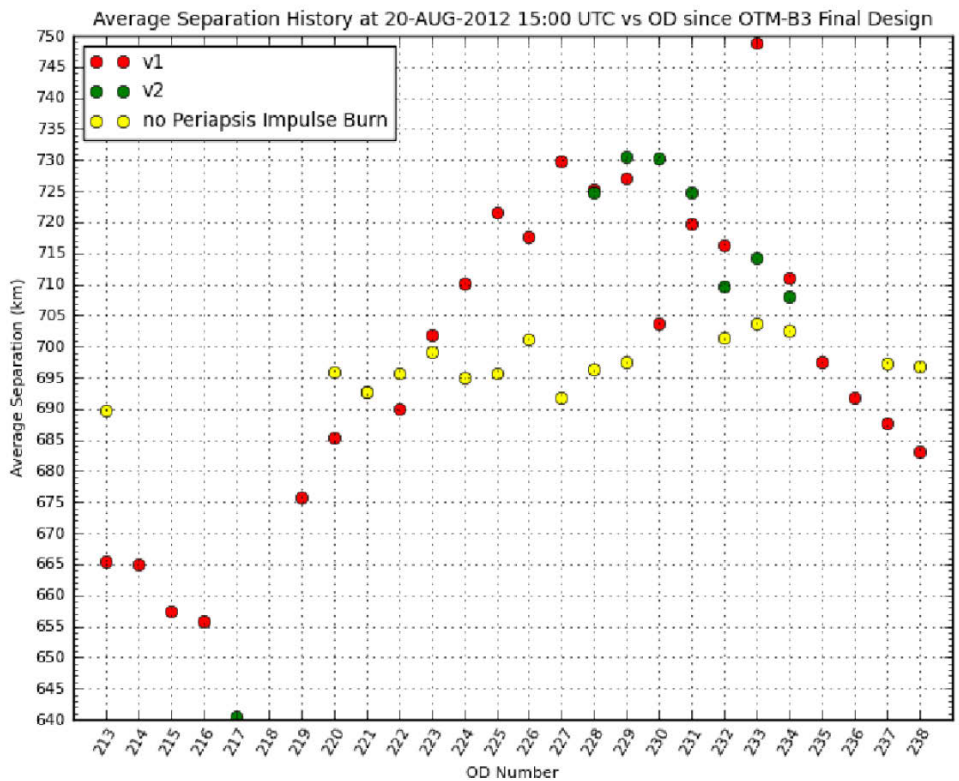
Orbit Determination Activities in Blue	All Activities for Two Spacecraft Except for OTM Support (GRAIL-A Only)

MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
OD for Maneuver R/T Monitoring	OD for Maneuver R/T Monitoring	ECM Design Project Approval		Sequence Timing Update if Needed
Maneuver R/T Setup	Maneuver R/T Setup	Daily OD	Daily OD	Daily OD
ECM Maneuver R/T Monitoring Quick Assessment OD Reconstruction Product Delivery Weekend OD	OTM Maneuver R/T Monitoring Quick Assessment OD Reconstruction Product Delivery Weekend OD	Develop Staffing Plan, Tracking Data Delivery Schedule and OD Delivery Schedule for Next Week	ECM Covariance Analysis	
OTM Design	ECM Design			ECM R/T Monitoring Prep
Trajectory Prediction with/without OTM	ECM Design Navigation Internal Approval	ECM Design Validation	Trajectory Prediction with/without ECM	
ECM R/T Monitoring Prep				

Note: Activity Durations Approximate

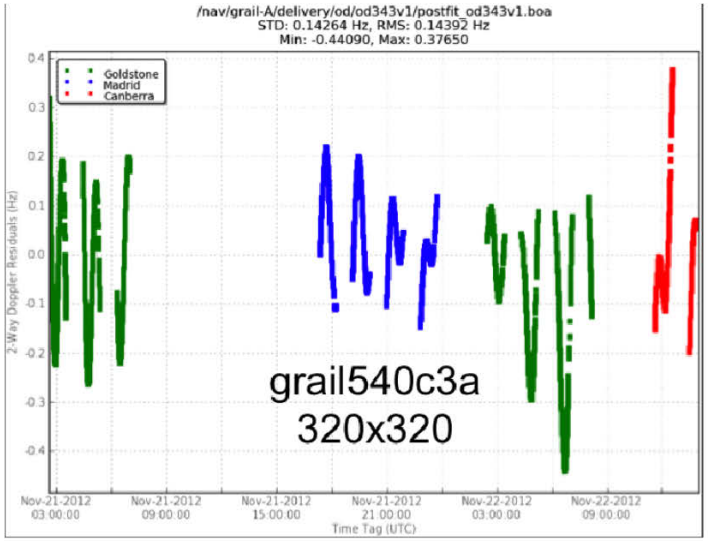
Low Beta Angle Phase Anomaly

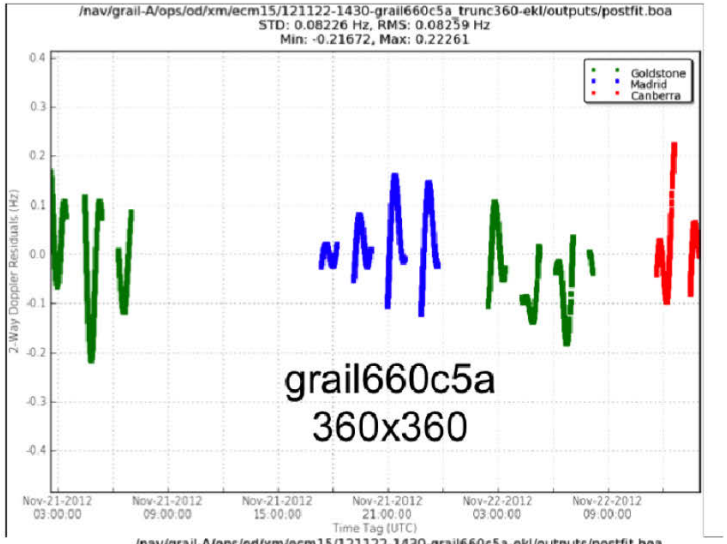
- Alarming drift observed in spacecraft separation for long term trajectory prediction during LBA Phase
  - As much as 5 km/day
- Extensive analysis found no evidence of a physical cause
- Traced to biasing caused by per-periapsis impulsive burn technique

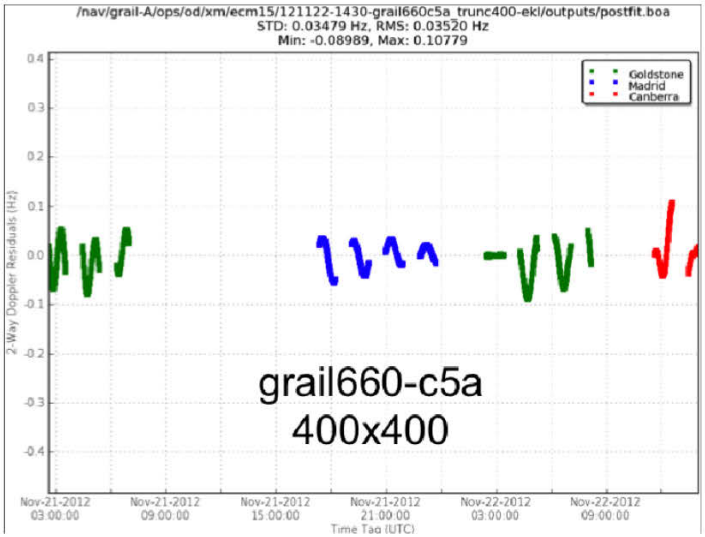


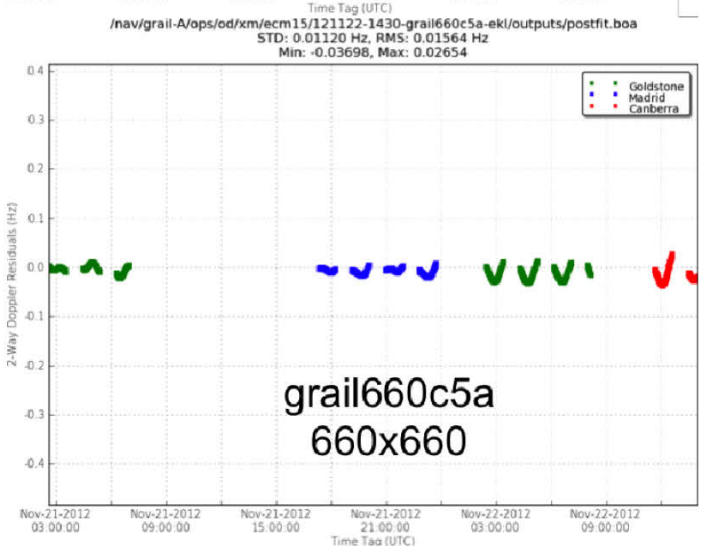
Gravity Model Evaluation - 1

Doppler Residuals with Various Gravity Models and Truncations



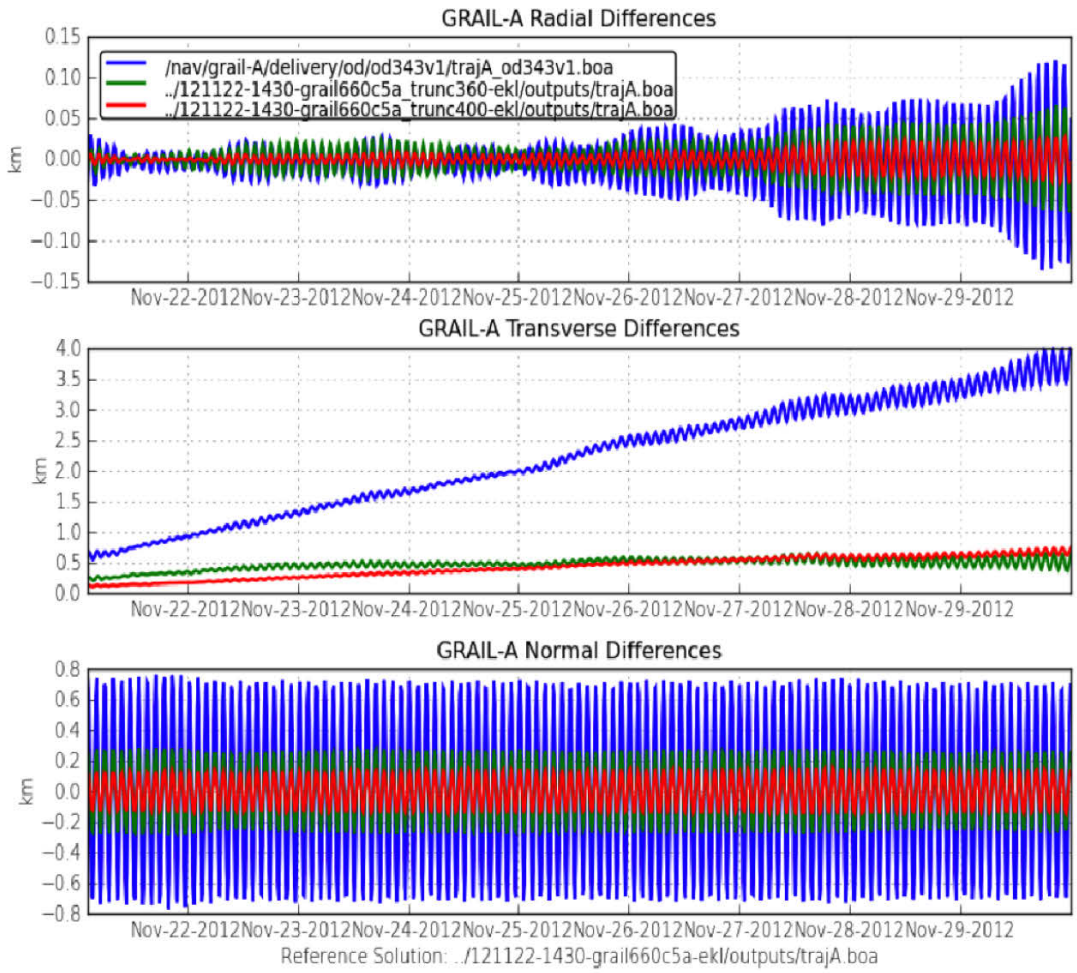






Gravity Model Evaluation - 2

Trajectory Prediction with Various Gravity Models and Truncations



grail540c3a
320x320

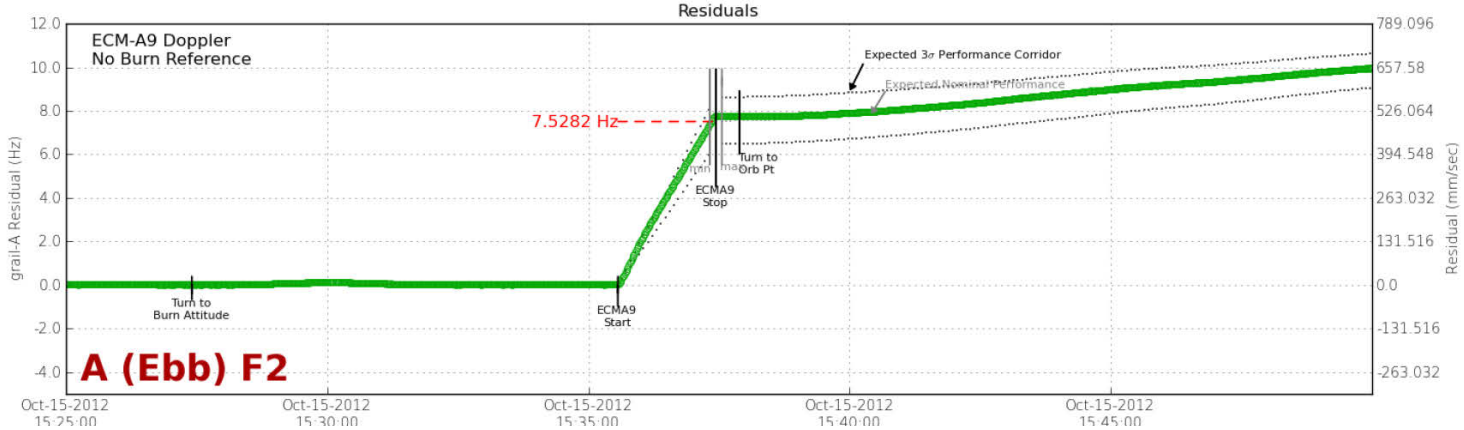
grail660c5a
400x400

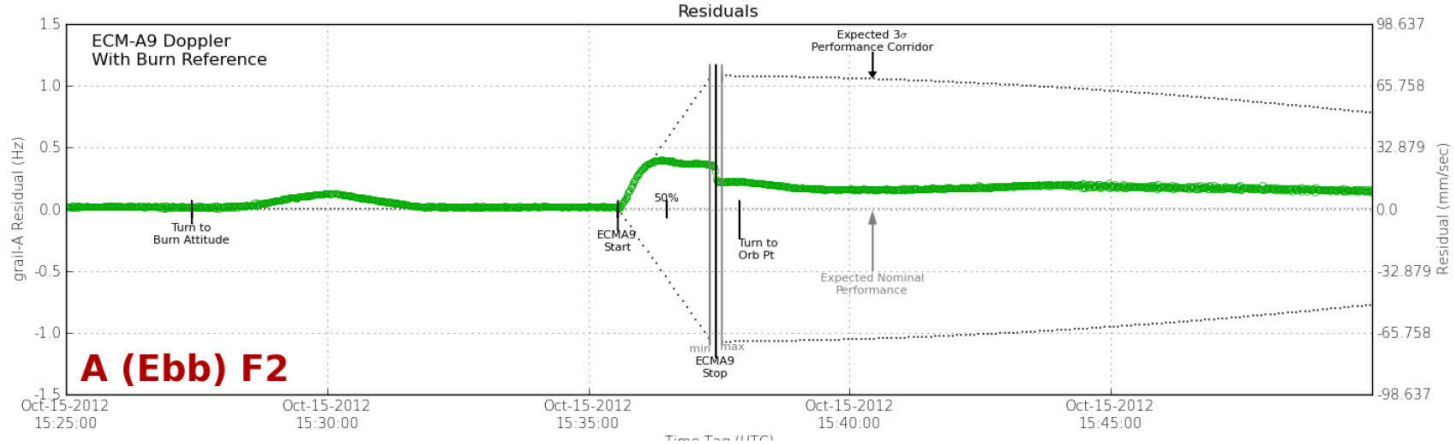
360x360

660x660

Maneuver Support

- Total of 56 maneuvers supported
- Maximum of four hours of post maneuver tracking for reconstruction
  - Frequently occurred during occultation or without two-way Doppler
- Real-Time maneuver monitoring



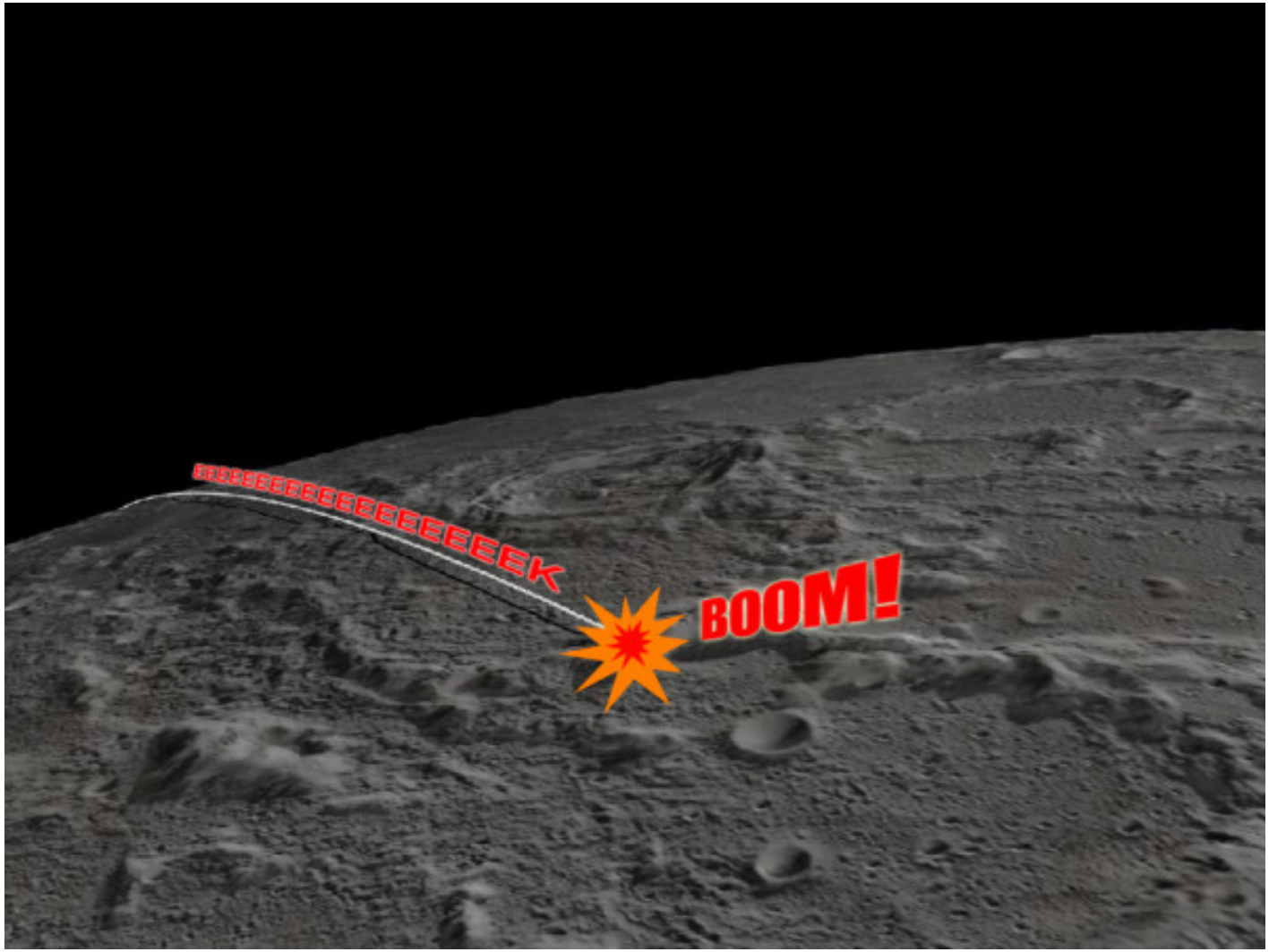


Conclusion

- The GRAIL Orbit Determination Team overcame significant challenges posed during operations for two spacecraft in low lunar orbit
  - Implemented an operational scenario which achieved project requirements despite the presence of significant errors in the lunar gravity models
  - Met challenging timelines which enabled implementation of the mission plan during the Science Extended Mission phase
- Delivered over 700 operational solutions
- Supported 52 maneuvers

- Project achieved virtually 100% of science acquisition goals for the Prime and Extended mission phases
- Lead to the development of significantly improved global lunar gravity model
  - Most accurate for any planetary body – including the Earth

Questions?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