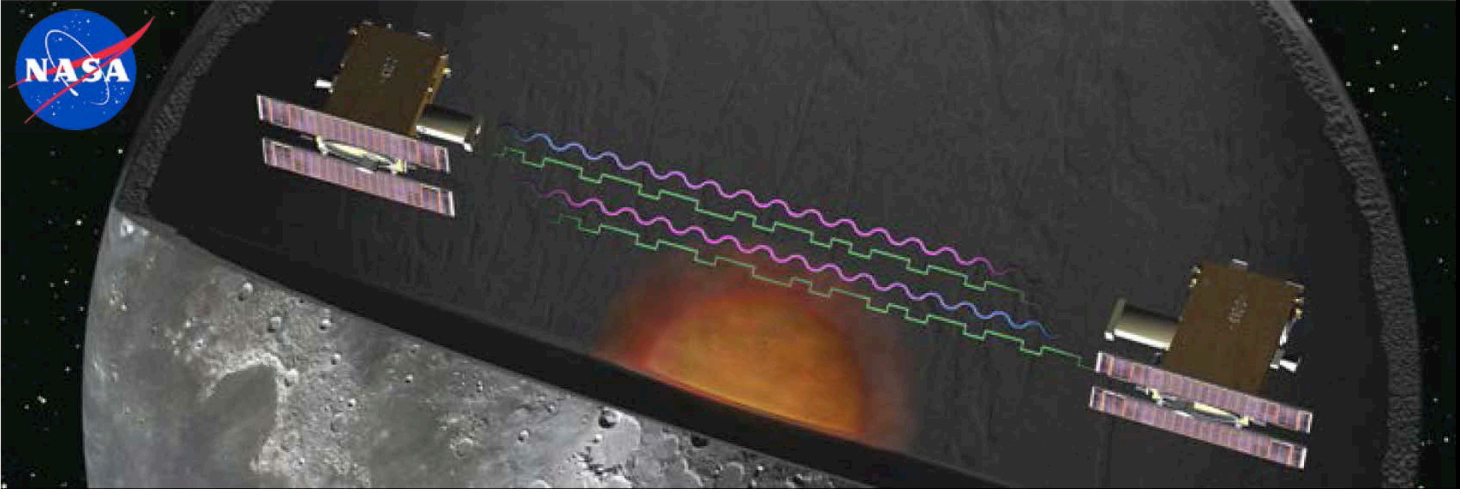

GRAIL

Gravity
Recovery
and
Interior
Laboratory

The Role of GRAIL Orbit Determination in Preprocessing of Gravity Science Measurements

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Introduction Preprocessing of GRAIL Gravity Science Measurements (1/2)

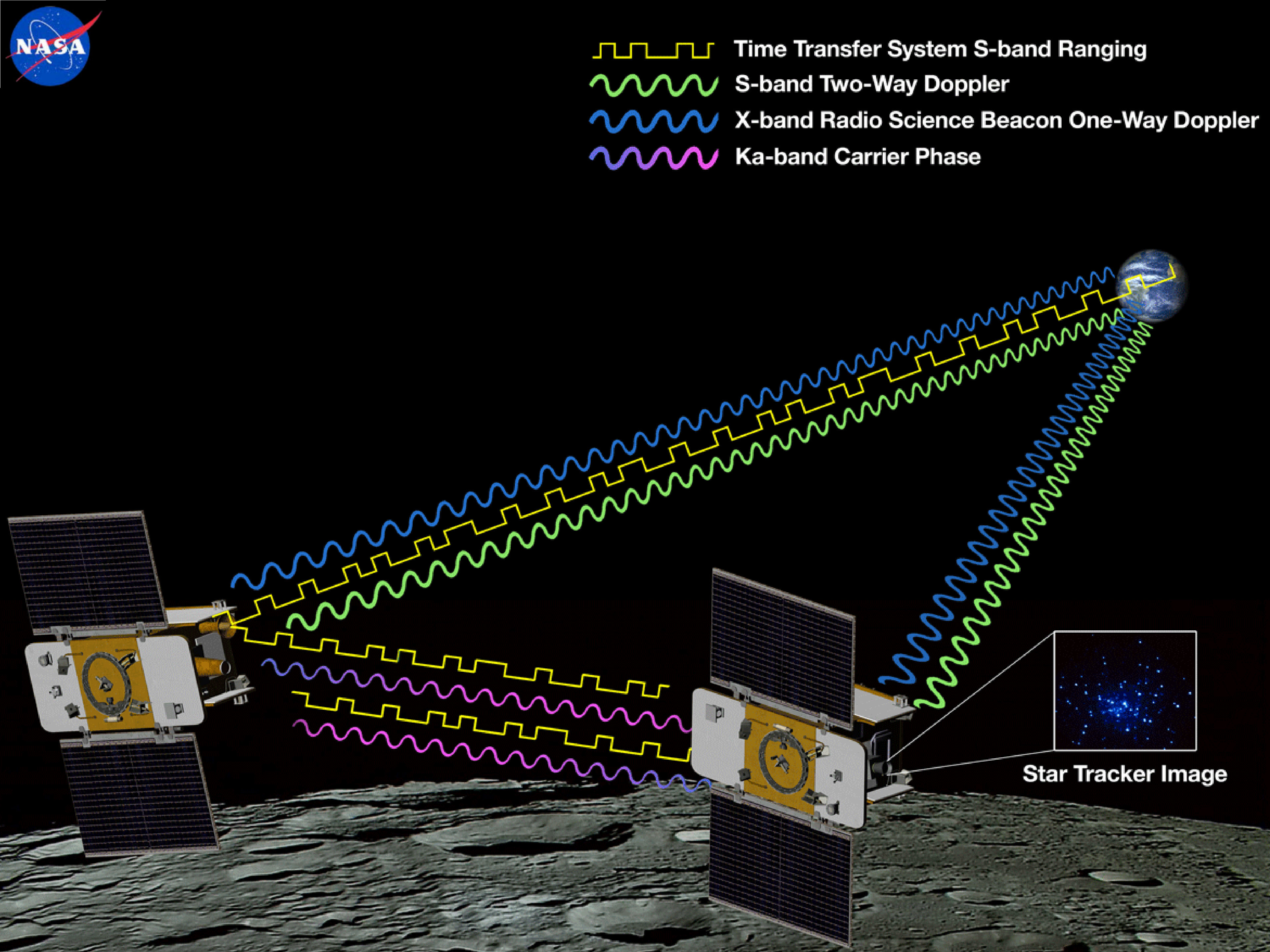
GRAIL
Discovery

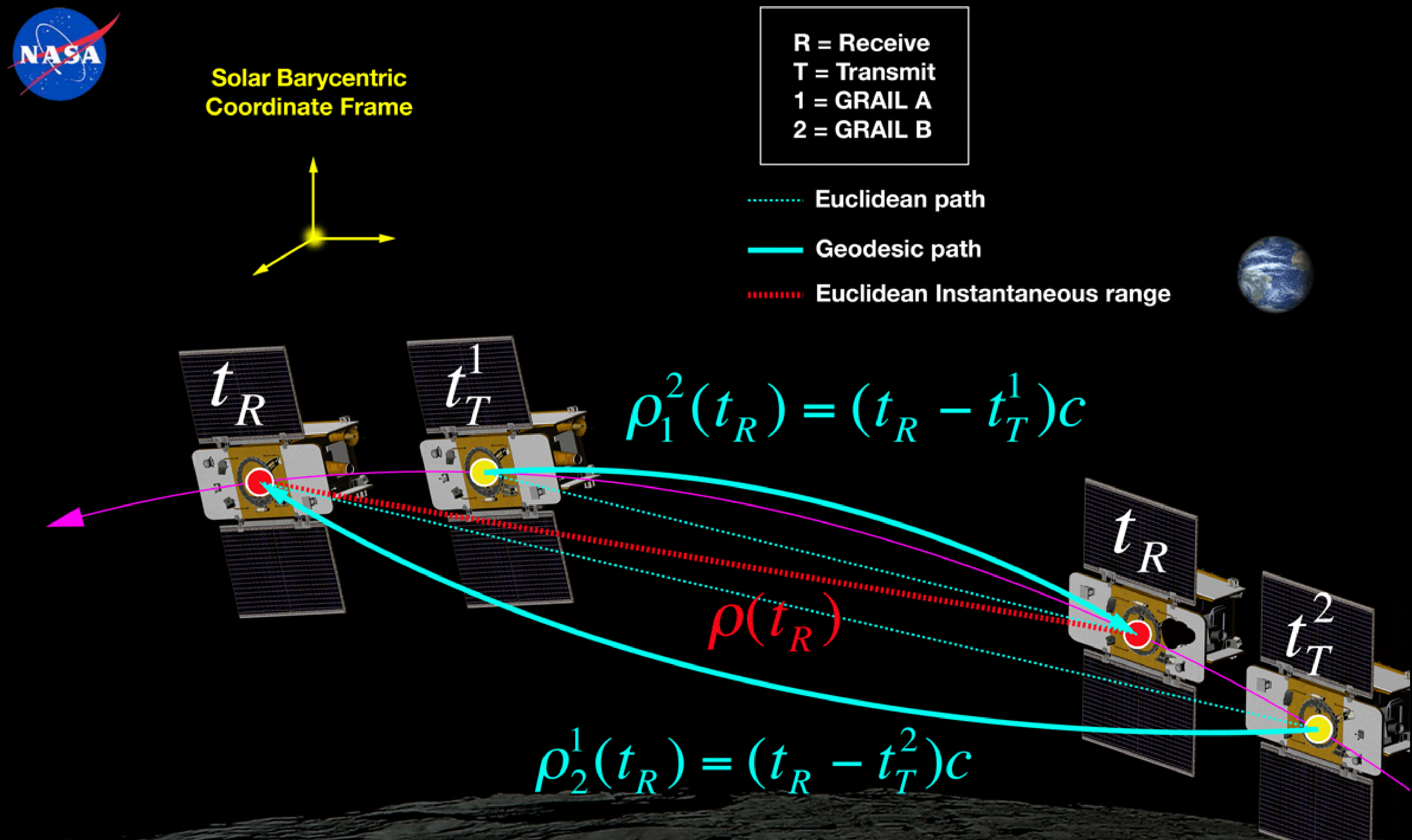
- Objective: Transform GRAIL inter-satellite Ka-band range measurements into instantaneous center-of-mass to center-of-mass Euclidean inter-satellite range in the Solar System Barycentric Coordinate Frame
- Ka-band transformations depend on spacecraft ephemerides, and Orbit Determination (OD) accuracy is limited by knowledge of lunar gravity
  - Lunar gravity of deep far side nearly unknown
  - Pre-GRAIL lunar gravity fields cannot provide required transformation accuracy – 1 μm threshold
  - Requires bootstrapping using GRAIL measurements to improve transformations and lunar gravity field

Introduction Preprocessing of GRAIL Gravity Science Measurements (2/2)

GRAIL Discovery

- Inter-satellite ranging system based on GRACE mission
  - GRAIL does not have GPS for timing and orbit determination
  - GRAIL includes a dedicated inter-satellite S-band ranging Time Transfer System (TTS) to meet science clock alignment requirements. Ka-band inter-satellite range measurement accuracy depends strongly on science clock alignment stability.
  - DSN tracking used for orbit determination and absolute timing
- Transformation of inter-satellite Ka-range measurements requires additional measurements with transformations that also depend on the accuracy of spacecraft ephemerides
  - Timing measurements, general relativity modeling
  - DSN tracking data (includes Ultra Stable Oscillator frequency data)
  - Ka-boresight vector calibration maneuver measurements

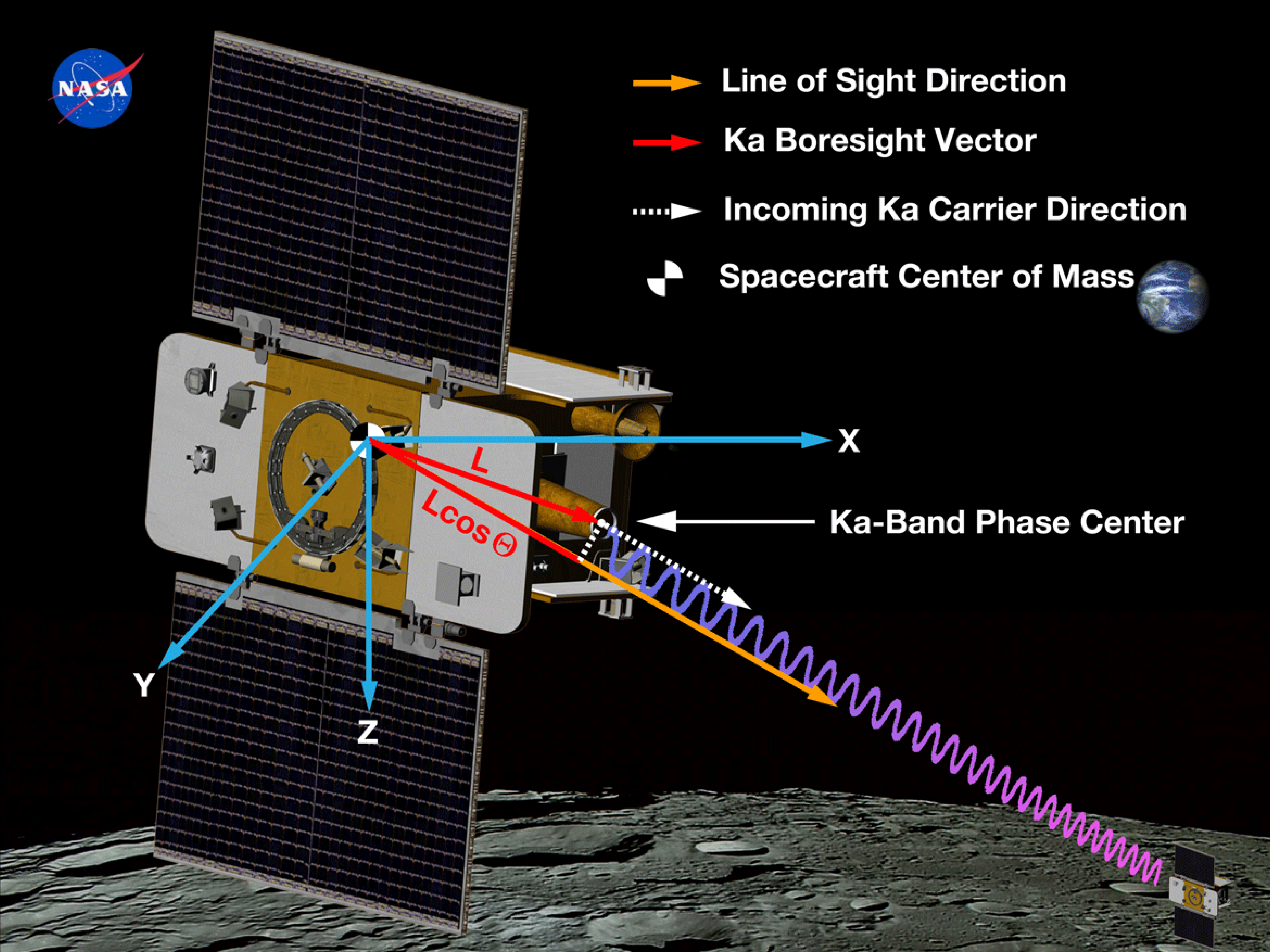

Time Transfer System S-band Ranging
S-band Two-Way Doppler
X-band Radio Science Beacon One-Way Doppler
Ka-band Carrier Phase
Star Tracker Image



Desired measurement is Euclidean instantaneous range

Time Of Flight (TOF) correction is the difference between Dual One Way Range (DOWR) measurement and Euclidean instantaneous range

$$\rho(t_R) = \rho_{dowr}(t_R) + \rho_{TOF}(t_R) = \frac{1}{f_1 + f_2}\left[f_1\rho_2^1(t_R) + f_2\rho_1^2(t_R)\right] + \rho_{TOF}(t_R)$$



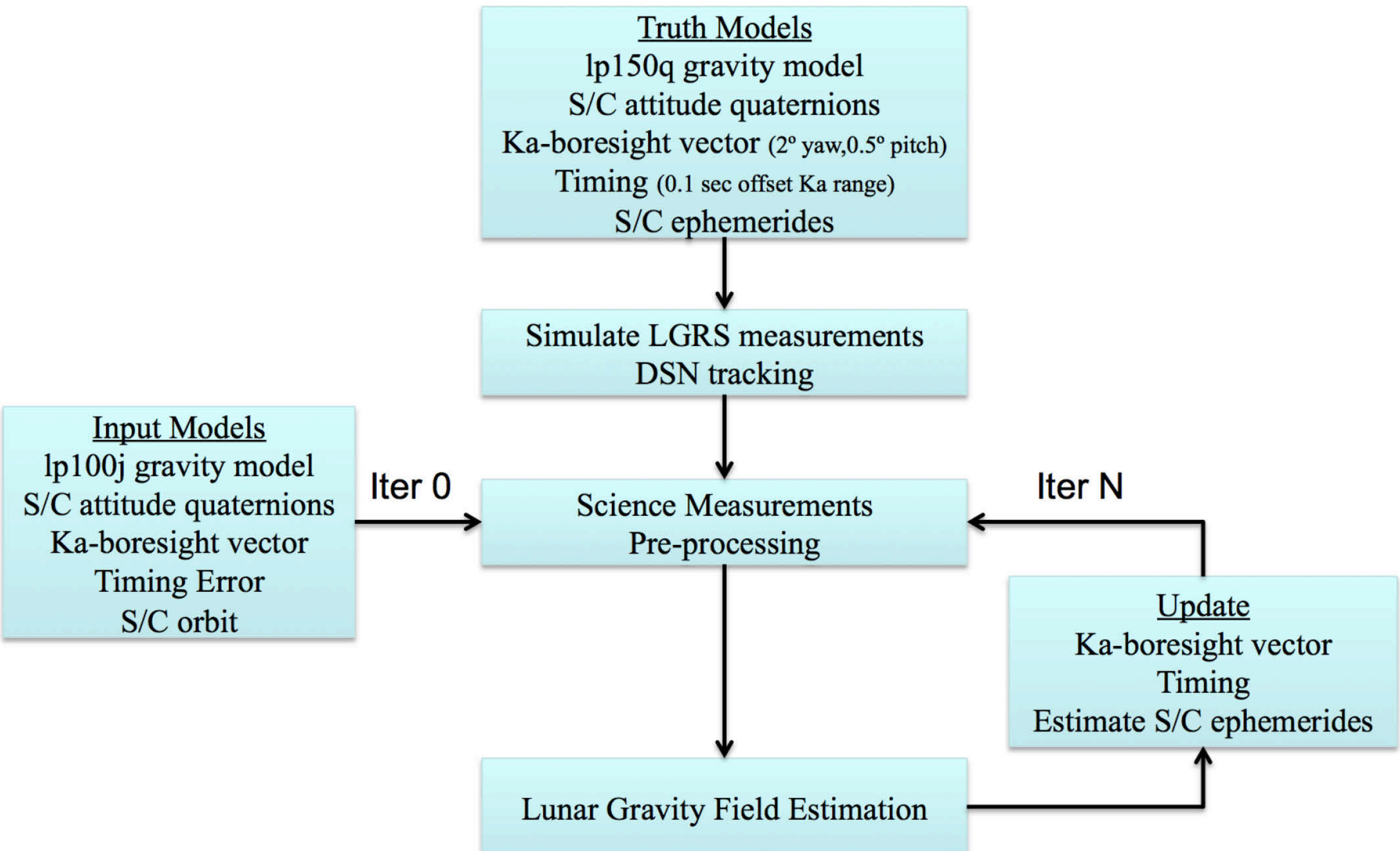
NASA
Line of Sight Direction
Ka Boresight Vector
Incoming Ka Carrier Direction
Spacecraft Center of Mass
X
L
Lcos Θ
Ka-Band Phase Center
Y
Z

Bootstrapping Strategy

- Include inter-satellite range-rate measurements in the orbit determination (OD) process to reduce relative orbit error.
  - Immediately, relative error for pre-GRAIL gravity fields decreases to 3 m level which reduces the Time Of Flight correction error to ~2 μm
- Bootstrapping steps:
  1) Transform gravity science measurements using latest OD solution
  2) Update gravity field and estimate absolute time tag errors for inter-satellite Ka-range measurements
  3) Update Ka-boresight vector
  4) Redo OD with latest gravity field
- Continue bootstrapping until convergence
- Pre-flight simulation used to validate bootstrapping strategy

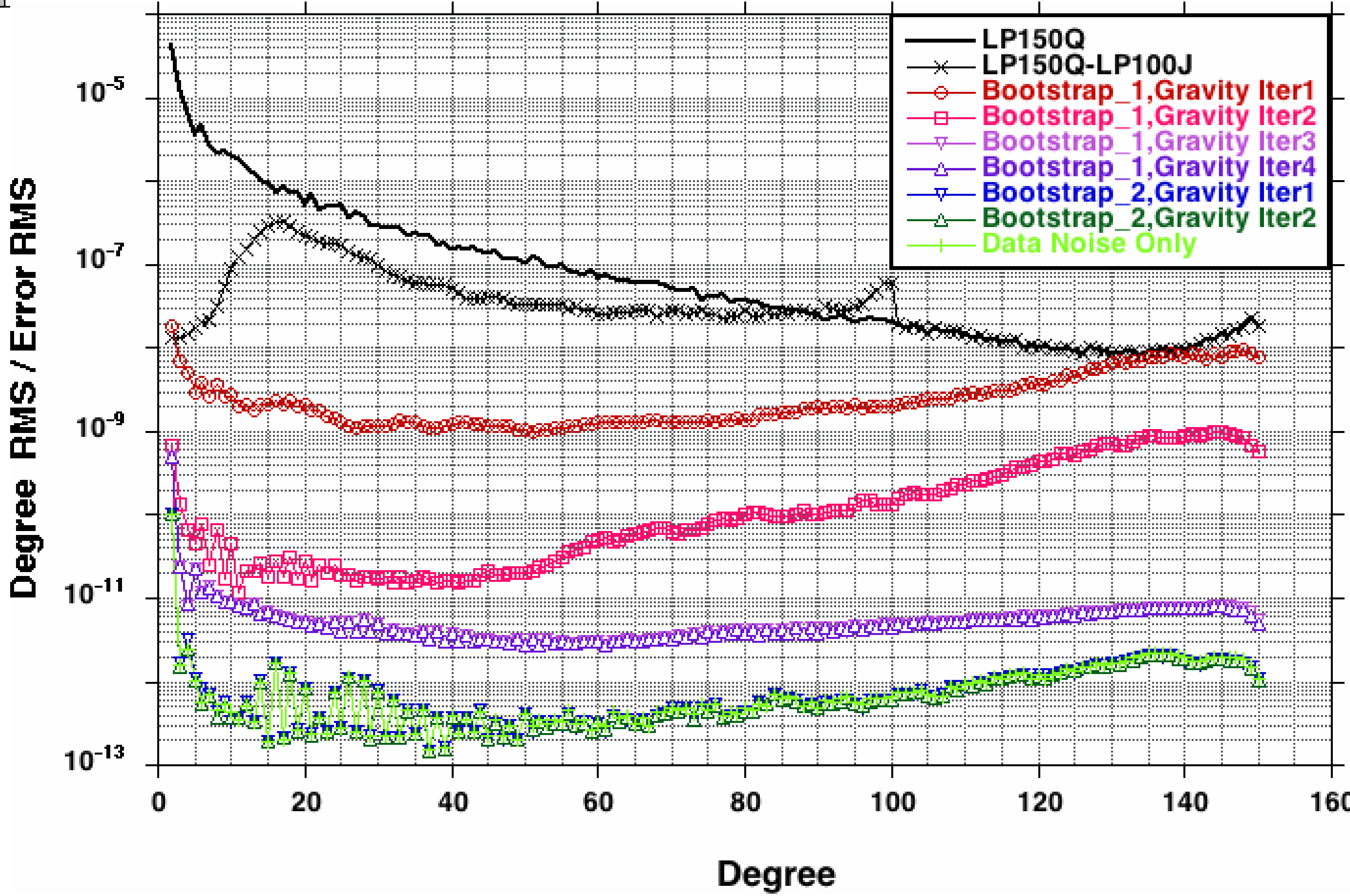
Bootstrapping Simulation

GRAIL
Discovery



Simulation Results (1/2)

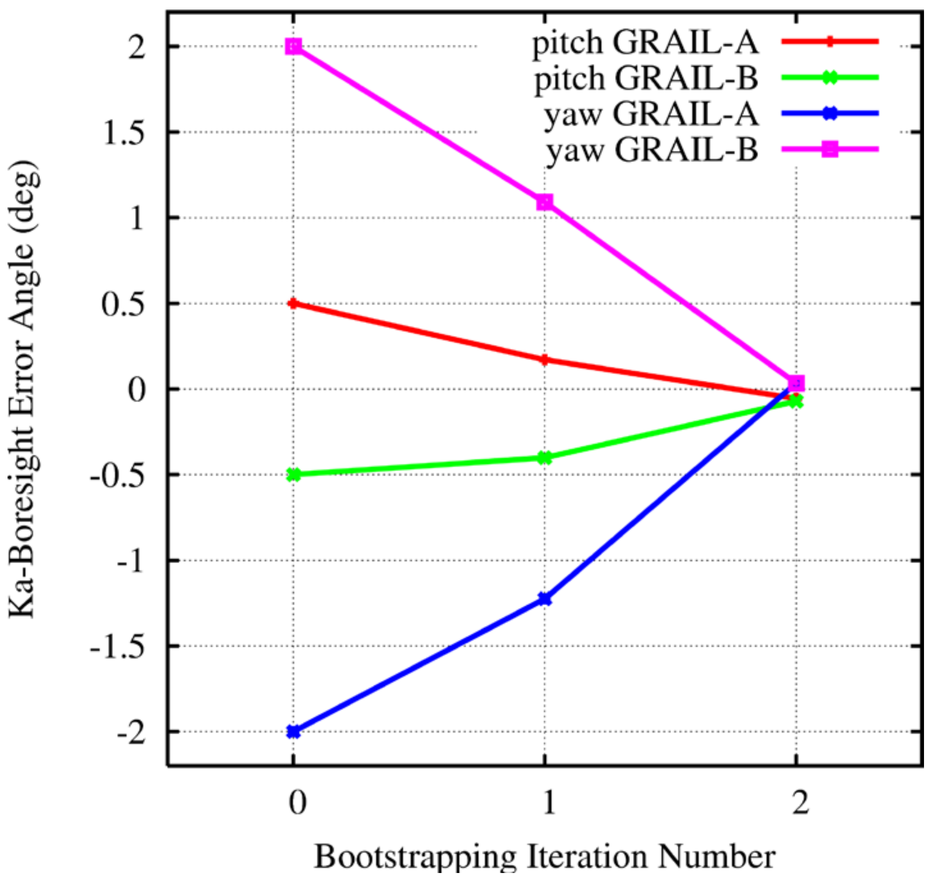
GRAIL
Discovery



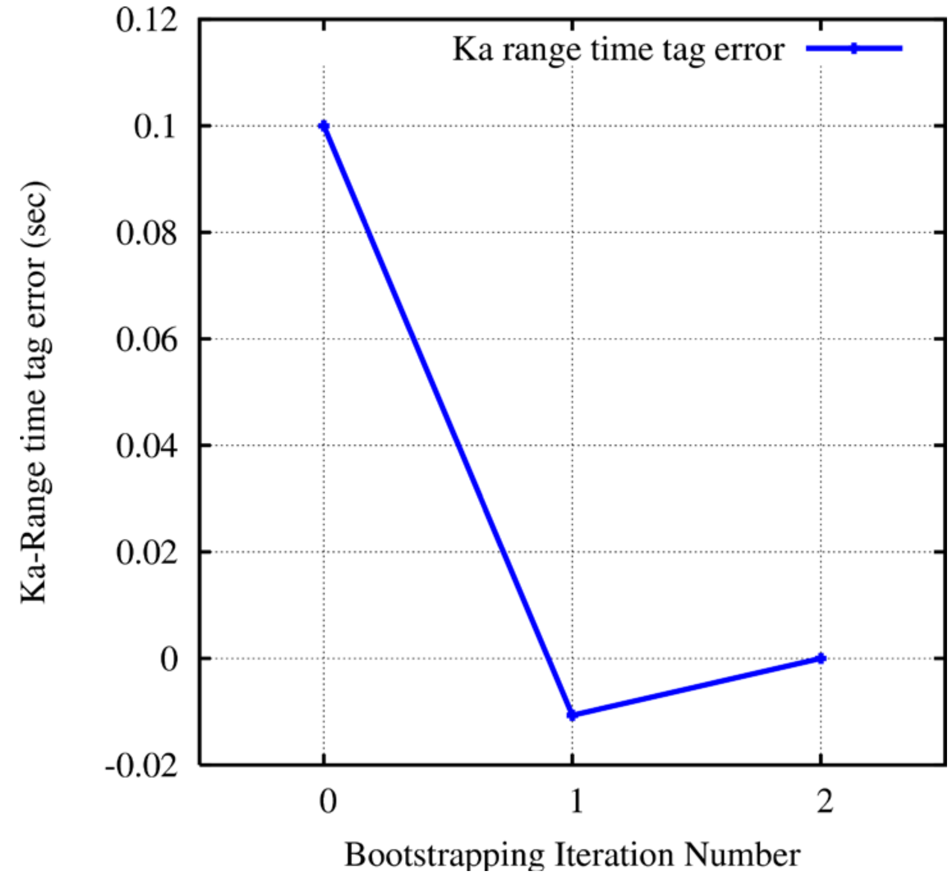
Simulation Results (2/2)

GRAIL
Discovery

Ka-Boresight Vector Error



Ka-range Time Tag Error



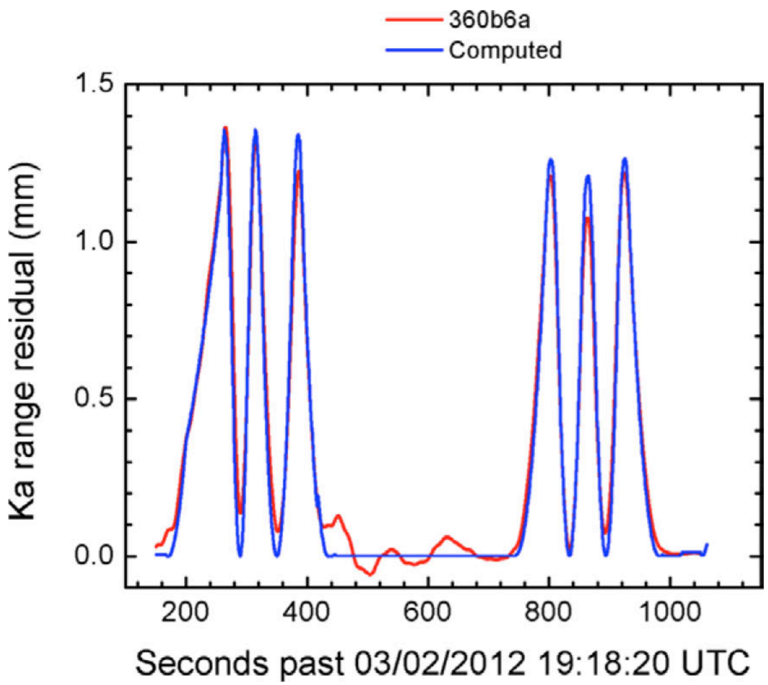
Flight Results

- Bootstrapping required increasing the resolution of the estimated gravity field at each iteration to fit low altitude data
  - In primary mission orbital altitude above the lunar surface varied from 30 to 100 km (extended mission 2 to 40 km)
- Bootstrapping has nearly converged but higher resolution gravity field of combined primary and extended mission data will be used to confirm convergence.
- DSN tracking, Ka range-rate residuals and spacecraft ephemerides improve with each bootstrapping step (Fahnestock paper AAS 13-271)
- Correlation of recovered lunar gravity field with LRO lunar topography improves at each bootstrapping step. (Park paper AAS 13-272)

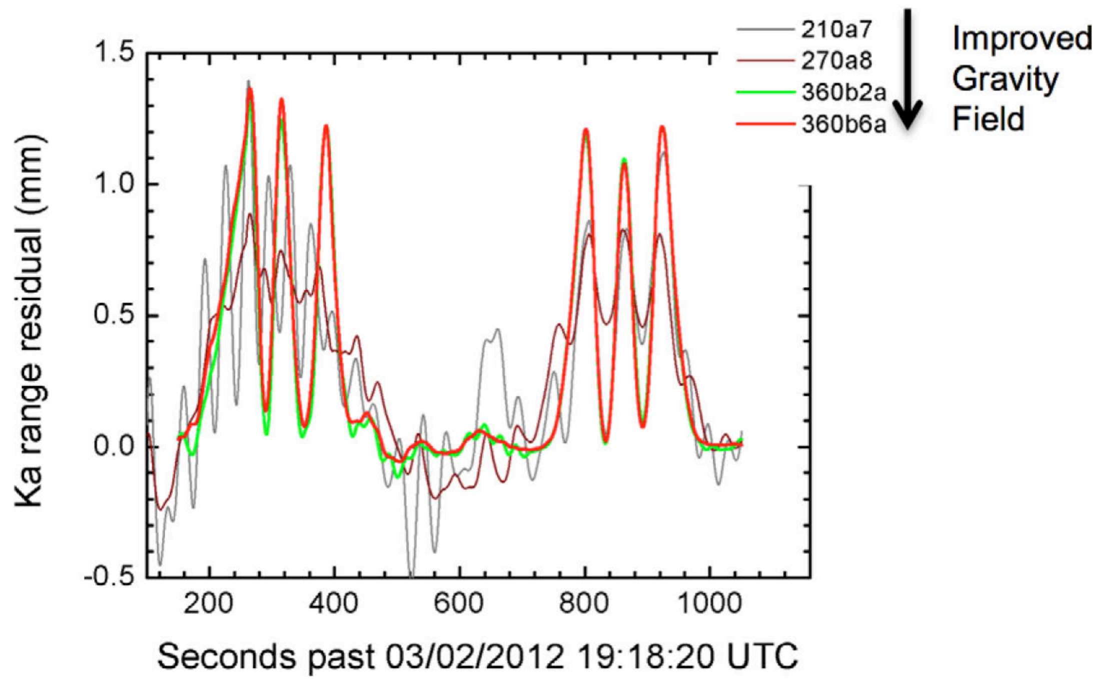
Flight Results (Ka-Boresight Vector Recovery)

GRAIL
Discovery

Recovered Ka-range Residual vs Computed



Evolution of Recovered Ka-range Residuals during Bootstrapping (Primary Mission Data)



Summary

- Orbit Determination is a pivotal step in the bootstrapping process because most GRAIL science data transformations depend on spacecraft ephemerides
- The basic strategy used in the bootstrapping process was validated via simulation
- During flight the bootstrapping process required higher resolution estimated gravity fields at each iteration to fit low altitude data
- The bootstrapping process has converged for the primary mission, but further bootstrapping is needed for the extended mission