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OSIRIS-REx
ASTEROID SAMPLE RETURN MISSION

OSIRIS-REx Precision Orbit Determination

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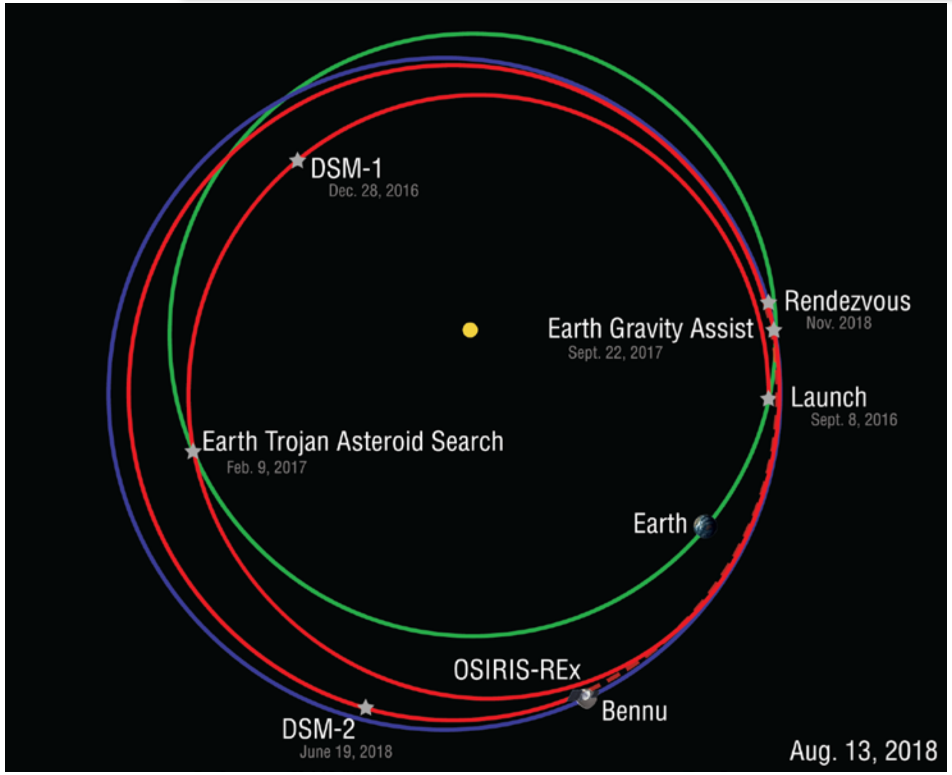
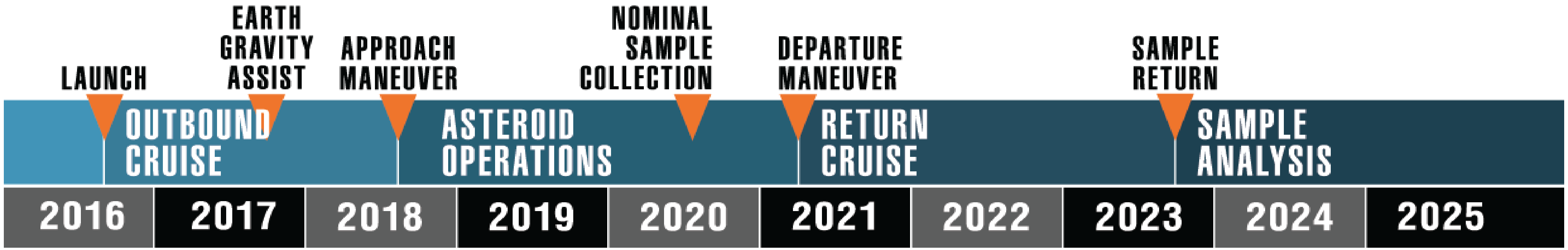
OSIRIS-REx Overview



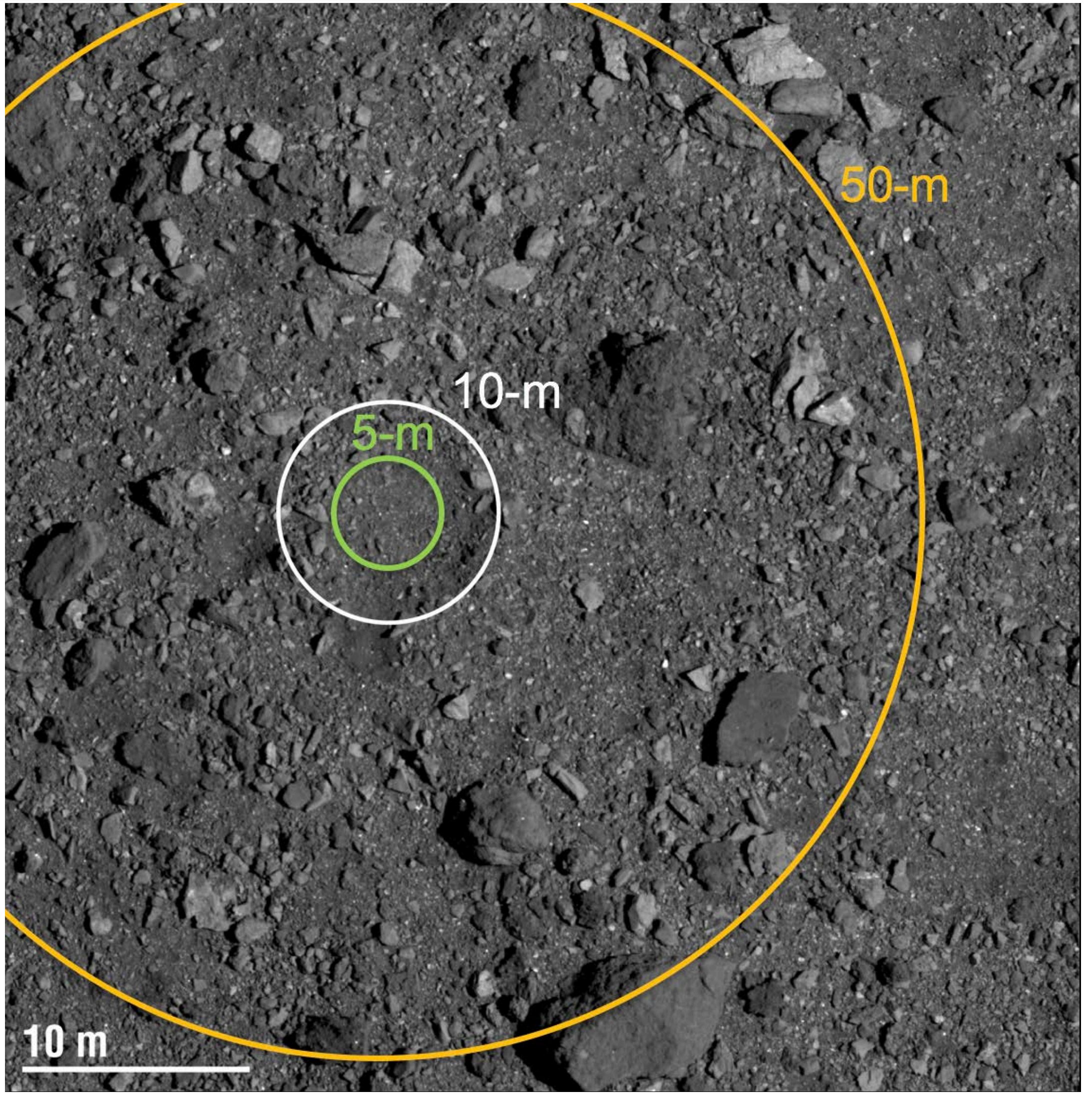
- **O**rigins
  - Return and analyze a sample of pristine carbonaceous asteroid regolith
- **S**pectral **I**nterpretation
  - Provide ground truth for telescopic data of the entire asteroid population
- **R**esource **I**dentification
  - Map the chemistry and mineralogy of a primitive carbonaceous asteroid
- **S**ecurity
  - Measure the Yarkovsky effect on a potentially hazardous asteroid
- **R**egolith **Ex**plorer
  - Document the regolith at the sampling site at scales down to the sub-cm

OSIRIS-REx MISSION OPERATIONS TIMELINE



The (101955) Bennu Environment

- Orbit Determination (OD) prediction performance and covariance realism vital for science observation planning and Touch-and-Go (TAG) deliverability.
  - Science: targeted pointing during imaging.
  - TAG: Orbit Departure Maneuver (ODM) and Check Point (CP).
- Surface environment has significant hazards within original TAG requirement of 50 m diameter.
  - Largest hazard-free sites are no larger than 15 meters diameter.
- Teams driven to improve performance to be able to make TAG successful.



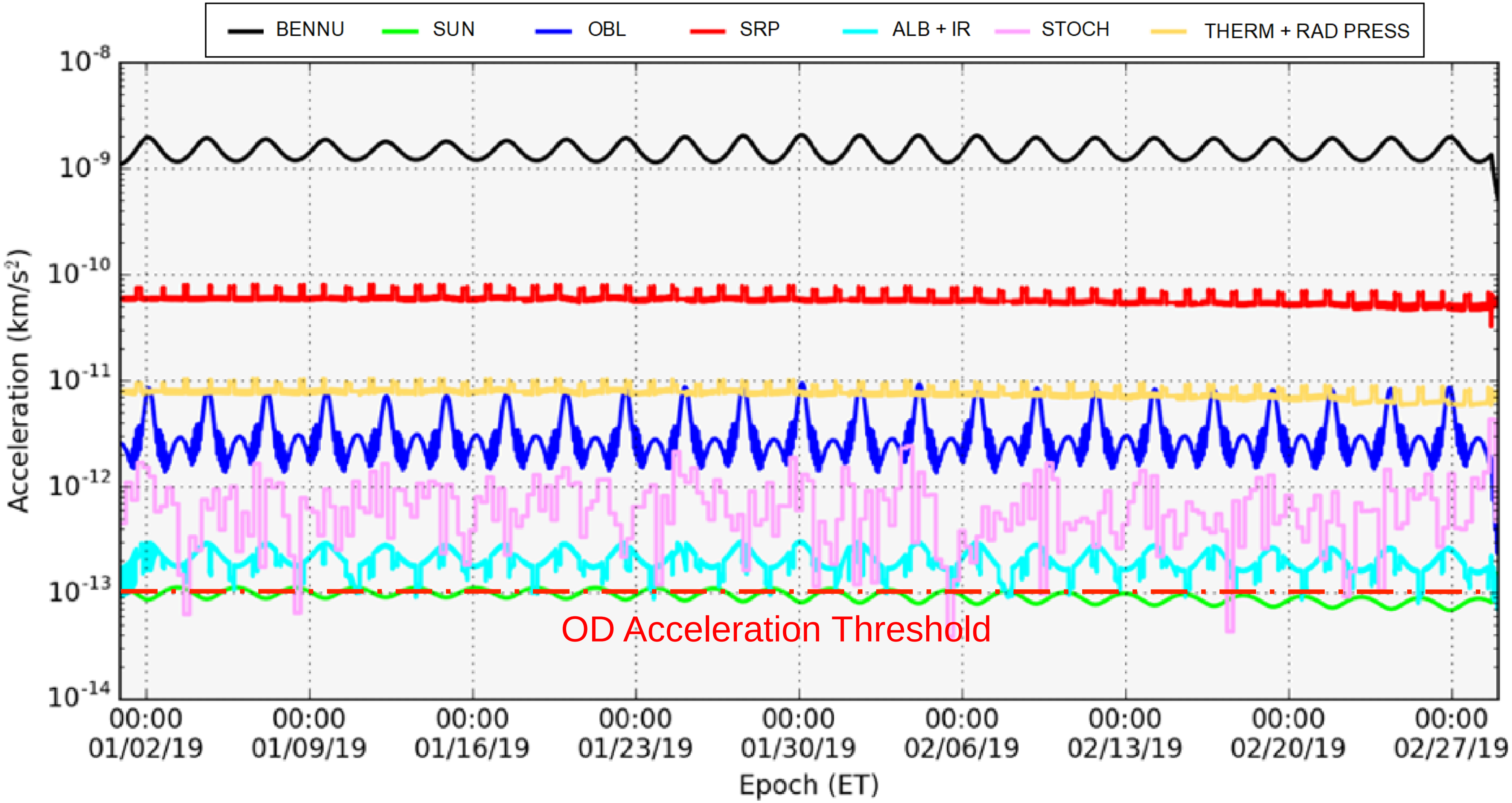
Navigation Challenges

- Bennu is the smallest object ever orbited.
  - Orbital velocities are on the order of cm/sec.
  - Small perturbations and force mismodeling greatly impact prediction performance.
- Strong correlations exist when performing OD around Bennu.
  - Solar Radiation Pressure (SRP) and S/C Thermal Re-Radiation Pressure (TRP) mismodeling induces a radial acceleration error that can be masked by Bennu's gravitational parameter (GM).
  - Antenna pressure/thrust as well as Bennu Albedo and IR have similar radial acceleration component greater than the estimated uncertainty in GM throughout all orbital phases.
  - Shape model scale directly impacts GM and trajectory reconstruction consistency.
  - Landmarks only on sunlit side can bias trajectory reconstruction, GM, SRP and shape model scale estimates.

Navigation Strategy

- OD team set the acceleration modeling threshold to be $1.0x10^{-13}$ km/sec^2.
  - Pre-approach covariance analysis showed ability to estimate accelerations at this level.
  - Need to understand all forces at this level to believe Bennu physical parameter estimates.
- Use of long exposure stellar images combined with short exposure images of the Asteroid provided accurate camera attitude information.
  - Gave confidence in the pointing used for landmark navigation.
  - Helps to de-correlate the camera pointing from other estimated parameters.
- Shape Model Evaluation
  - Pole orientation and PM, Center-of-Figure to Center-of-Mass Offset, Landmark Scaling and Locations, Shape model frame to spin-axis offset.
  - Bennu has a known YORP acceleration of the rotation rate derived from lightcurve data over the last few decades.
  - Estimated NPA rotation, but none has been detected to date.

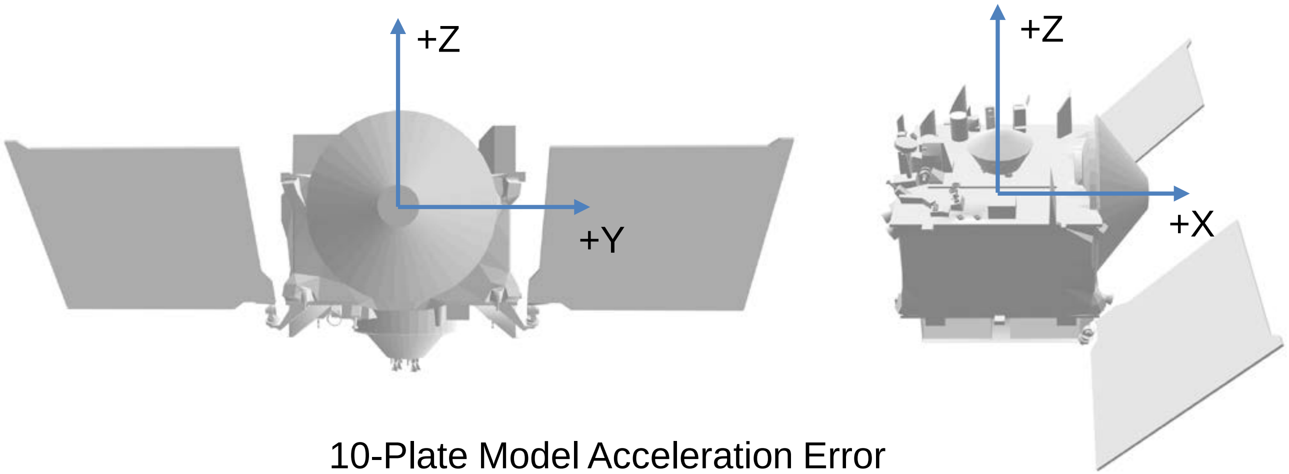
Accelerations during Orbital-A



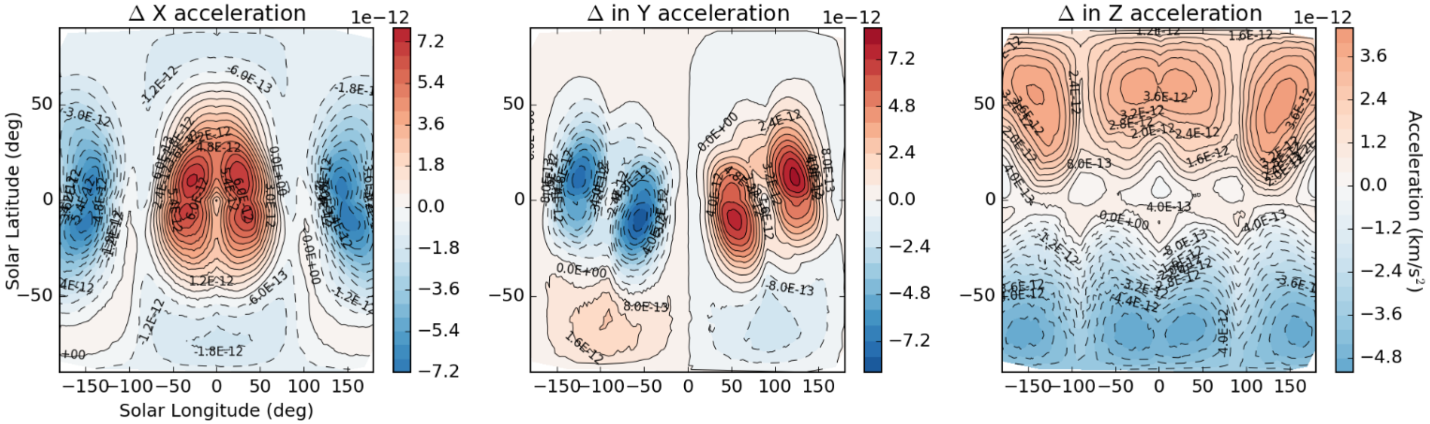
- Bennu GM
  - ~1.5E-9 km/s^2
- SRP
  - ~6E-11 km/s^2
- TRP
  - ~8E-12 km/s^2
- OBL
  - ~4E-12 km/s^2
- Rad. Press
  - ~2E-13 km/s^2
- IR
  - ~2E-13 km/s^2
- Sun
  - ~1E-13 km/s^2
- ALB
  - ~1E-14 km/s^2

OSIRIS-REx SRP Modeling

- Sun-point attitude was well characterized throughout Cruise with 10-Plate Model.
- Mismodeling evident in late Approach
  - S/C state uncertainties reduced from 100's of meters during Cruise to <10 meters.
  - Revealed Earth-point attitude error.
- Ray-traced model using a high fidelity shape model was investigated
  - Improved understanding of potential SRP errors at various attitudes.
  - Indicated 10-Plate model had an error > 1.0×10^{-12} km/sec^2 at Sun-Point, Nadir-Point and Earth-Point.
  - Updated modeling for improved prediction performance 2-fold.



10-Plate Model Acceleration Error



New SRP model reduced average state error over 5-day predicted span during Orbital-A from 19.6 m to 7.2 m in transverse

Trajectory Prediction Performance

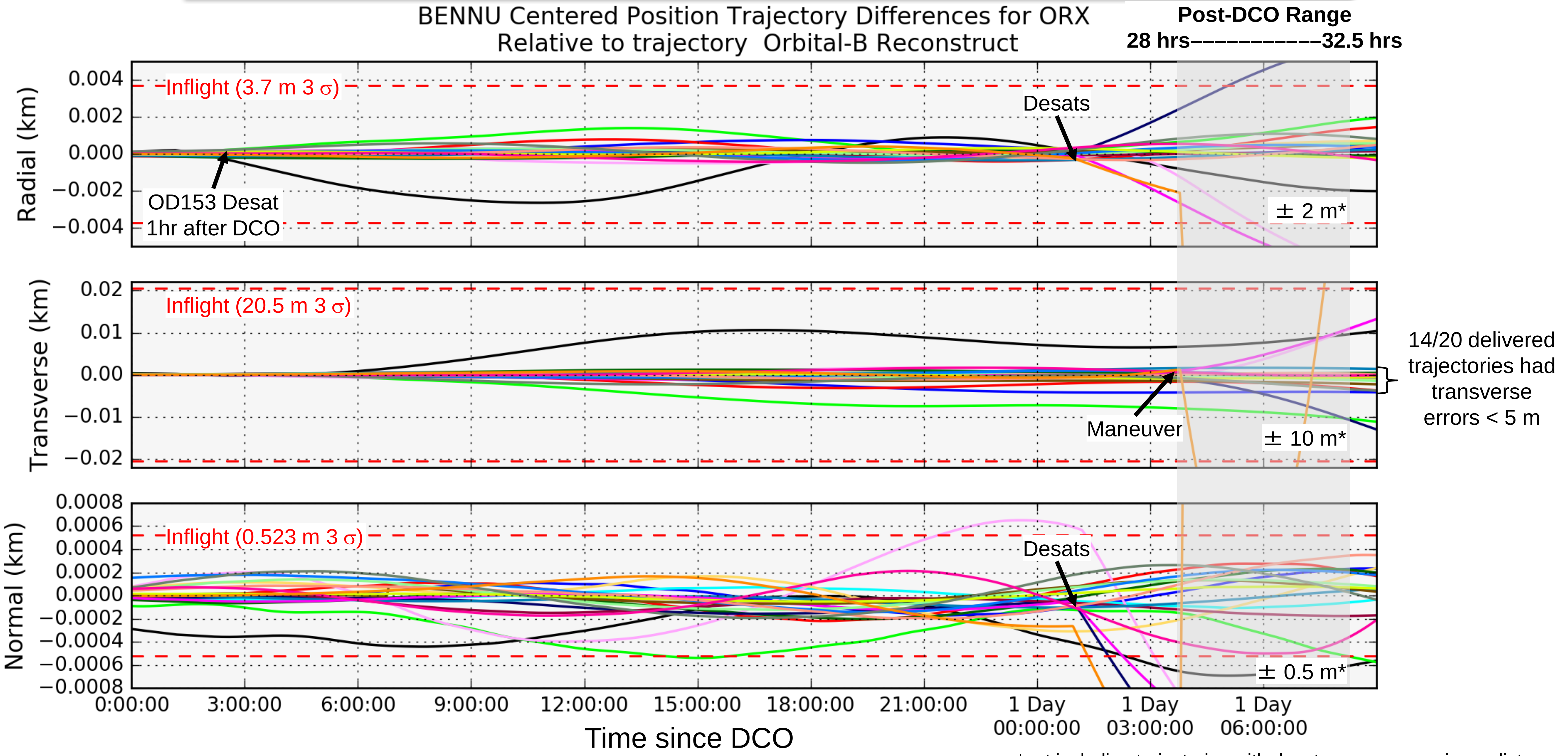
- Predicted trajectory errors during every phase outperformed pre-encounter expectations.
  - Predicted stochastic acceleration uncertainties updated during operations based on "Inflight" performance to improve science planning
- Navigation OD performance requirements for TAG (prelaunch):

*"OSIRIS-REx shall predict spacecraft position in Orbital B such that predictions 24 hours after OD cutoff agree to the current (definitive) position estimates to within **20, 85, and 7 meters** (goal - **6, 24, and 5 meters**), all 3σ values, in radial, along-track, and cross track (orbit-normal) directions, respectively."*

- **MAXIMUM** predicted position errors at 28-32.5 hours after DCO:

Phase	Radial (m)	Along-track (m)	Cross-track (m)
Orbital-A	± 4	± 15	± 1.5
Orbital-B	± 2	± 10	± 0.5
Orbital-C	± 3	± 9	± 5.0
Orbital-R	± 2	± 9	± 0.4

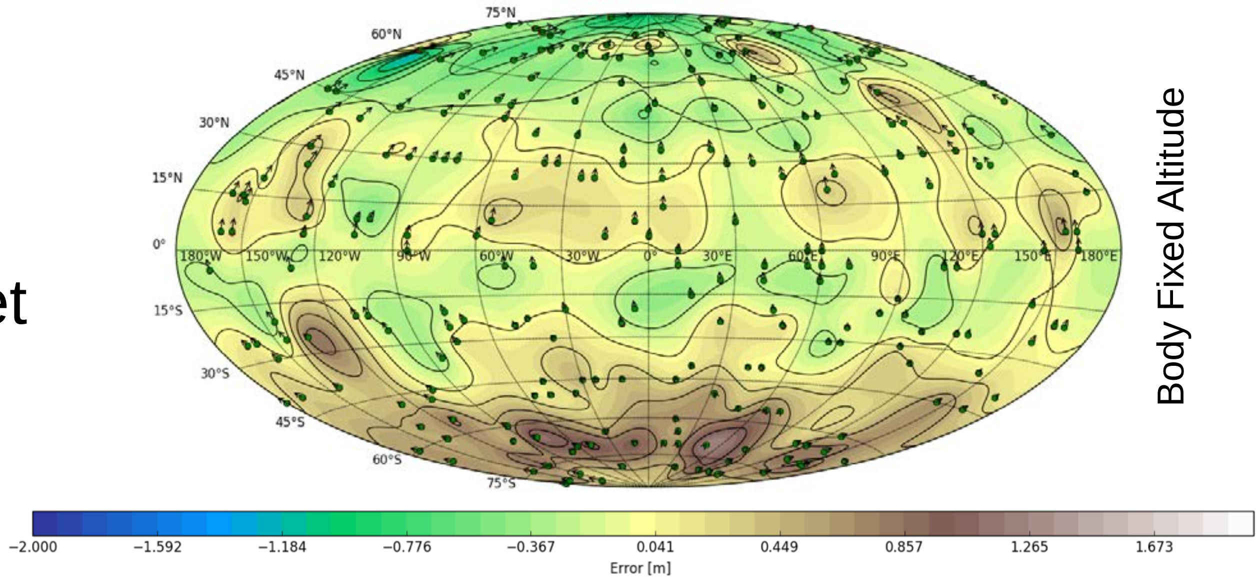
Orbital-B 28-32.5 hour Prediction

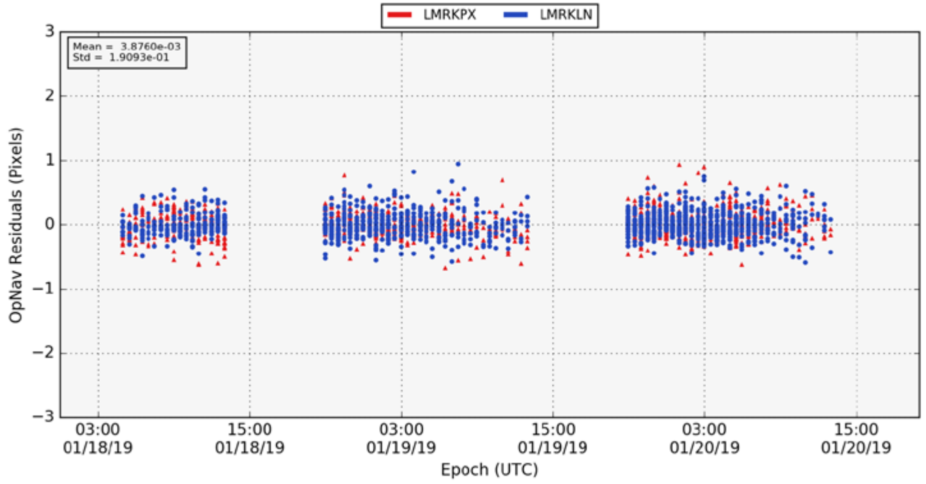


*not including trajectories with desats or maneuver in predict

Landmark Estimation

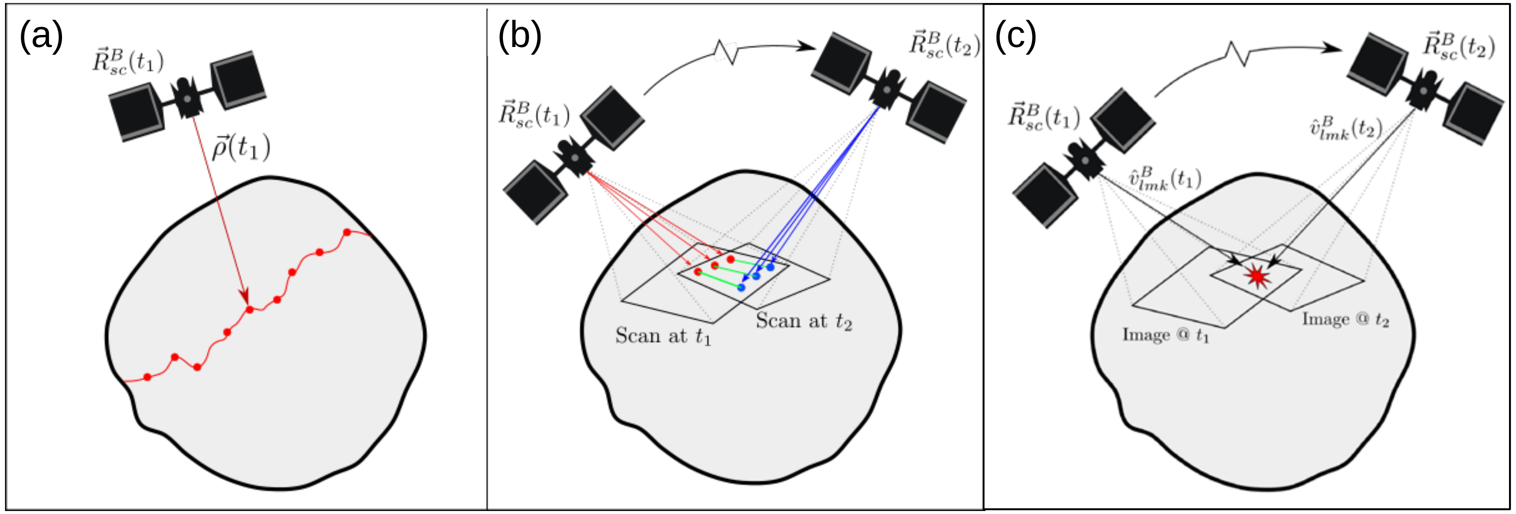
- Utilizing the shape model landmark locations as provided were within the defined requirements for navigation.
- Regional errors in the landmark maplet locations bias trajectory solutions.
- Estimation of the landmark locations improved the performance and produced more consistent results of Bennu estimated parameters.
- Reduced Landmark OpNav residual noise from 0.4 px to 0.2 px in Orbital-A.
  - Estimated landmark locations accurate to 10-15 cm.





Alternate Measurement Evaluation

- Radiometric, Center-finding, and Landmark based OpNavs primary measurement source.
- Alternate measurements investigated for comparisons
  - (a) Direct Altimetry
  - (b) Altimetric Crossovers
  - (c) Image Constraints
- Reconstructed trajectory solutions consistent to 10's of cm throughout mission phases.



Direct Altimetry

- Requires high fidelity shape model.
- Instrument pointing error evaluation and bias estimates.
- **30 cm std residual**

Altimetric Crossovers

- Utilizes two overlapping LIDAR pointclouds.
- Removes shape dependence.
- **15 cm std residual**

Image Constraints

- Location of same landmark in two images.
- Removes dependence on landmark location.
- **10 cm std residual**

Conclusions

- OSIRIS-REx OD Team has spent significant effort to improve spacecraft modeling over the last year.
  - Improvements have been realized in Science Planning for site selection and TAG.
- Orbital phase trajectory prediction performance throughout operations beats all pre-arrival expectations.
  - Transverse Error: Requirement 85 m (3-sigma), Goal 24 m (3-sigma), Achieved 10 m (MAX).
- Improved OD prediction performance directly impacts TAG performance
  - Reduces expected NAV errors at ODM and CP by 50%.
  - Reduces TAG deliverability errors by 10-20%.
- Utilizing alternative measurements allows for more confidence in delivered trajectories accuracy.
  - Trajectory consistency throughout orbital phases is on the order of 10’s of cm.

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- Lockheed Martin Space Systems in Denver built the spacecraft and is providing flight operations.
- Goddard Space Flight Center and KinetX Aerospace are responsible for navigating the OSIRIS-REx spacecraft.

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