OSIRIS-REx Orbit Determination Covariance Studies at Bennu

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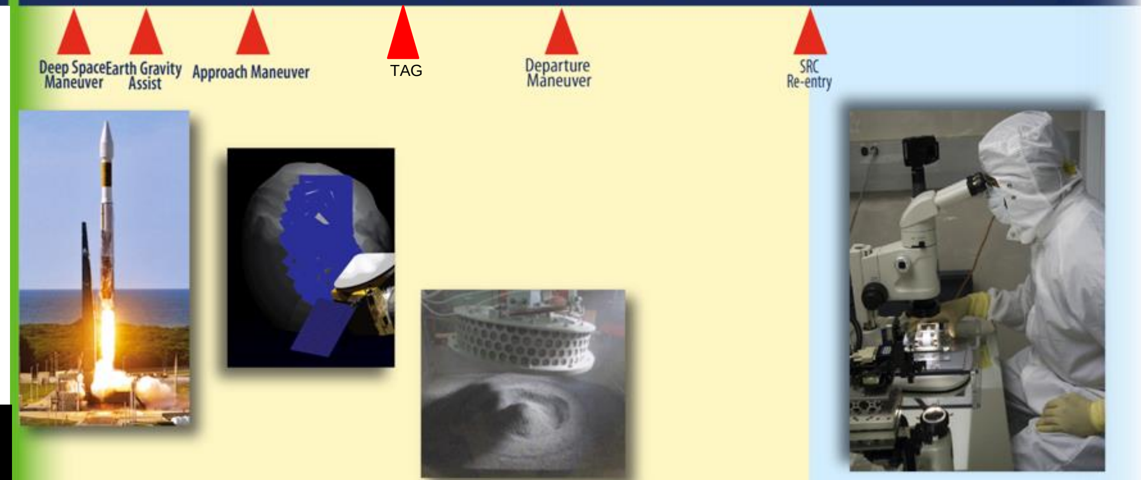
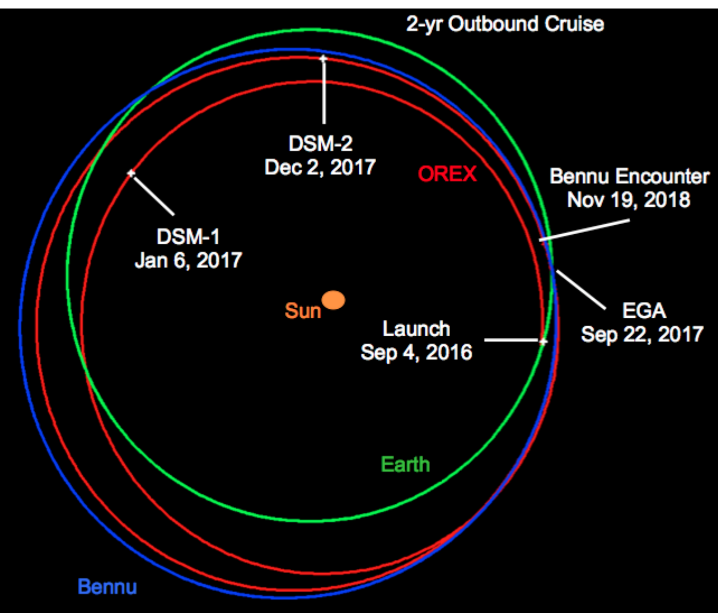
Origins Spectral Interpretation Resource Identification Security Regolith Explorer Mission



Institutional Partners

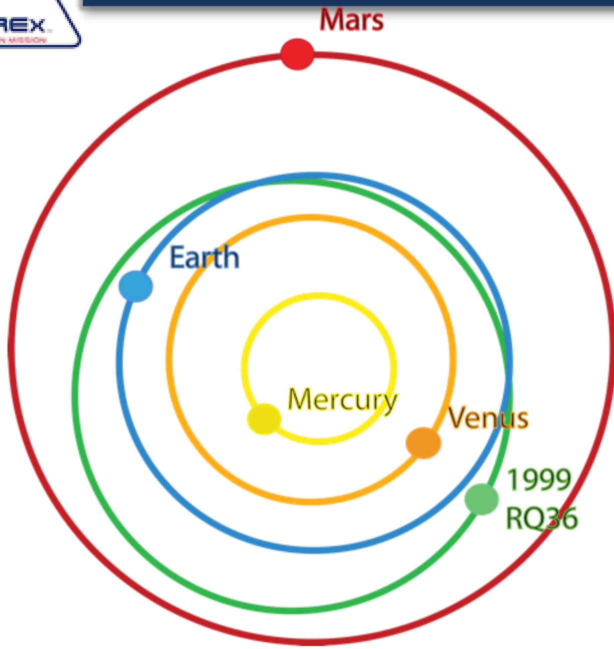
- Principal Investigator UA
- Project management — GSFC
- Spacecraft contractor/Mission Ops — LMSSC
- Instrument providers — UA, ASU, GSFC, CSA, MIT
- Navigation — KinetX / GSFC
- Science ops &science data center — UA SPOC

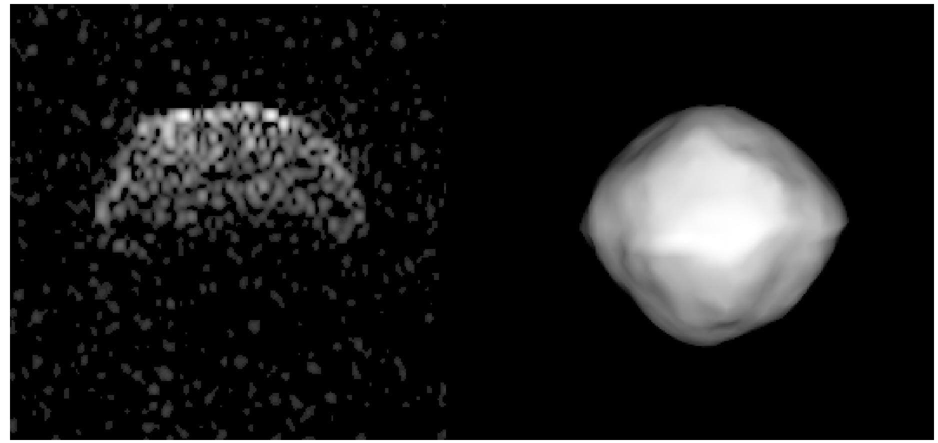


Mission Facts (7.1 year mission)

- Launch (ATLAS V–411), September 3rd, 2016 (39 day launch window)
- Earth Fly-By, September 2017
- Asteroid Approach Maneuver, October 2018
- Touch-And-Go (TAG) Sample Collection, August 2019
- Asteroid Departure Maneuver, March 2021
- Sample Return Capsule (SRC) Release, September 24, 2023
- 3-axis-stabilized spacecraft, with gimbaled solar arrays
- 5 Payloads & Touch-And-Go Sample-Acq-Mechanism (TAGSAM)

Asteroid Bennu Overview





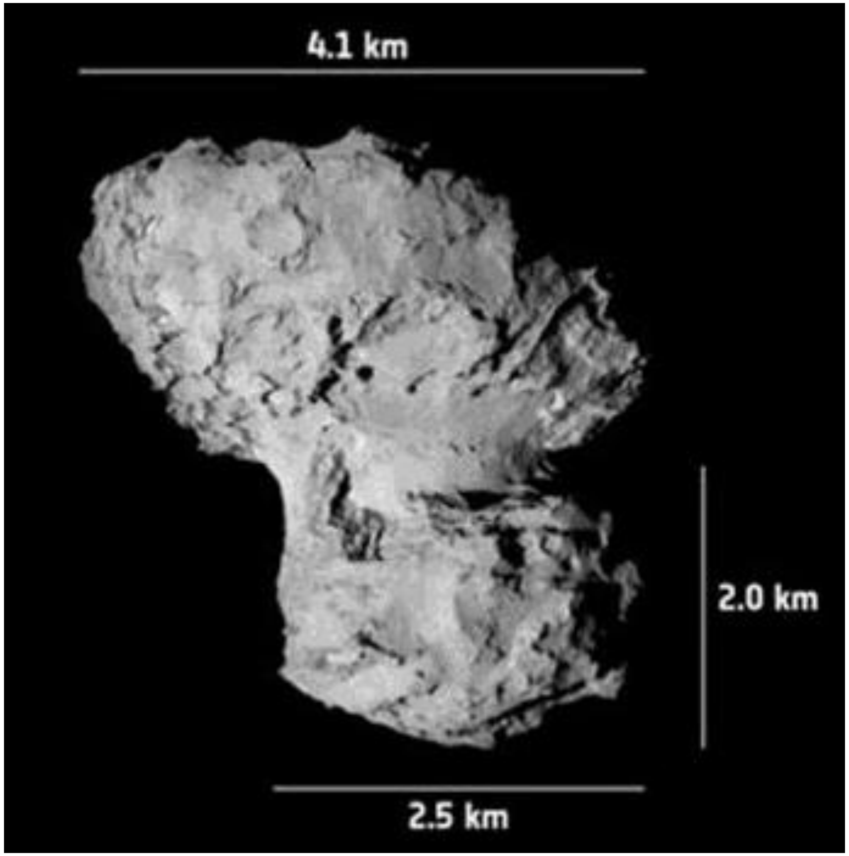
- Bennu (formally 1999 RQ36) is a primitive B-class, Near-Earth, carbonaceous (volatile-rich) asteroid, a class of object **never before visited by a spacecraft**
- Its **size, shape, and rotation state are known** from extensive characterization by the Arecibo Planetary Radar System
  - About 500 m diameter, 4.3 hr rotation period, 436.6 day orbit of Sun, 350 K maximum surface temperature, 3% geometric albedo, micro-gravity environment
- Study of this **Potentially Hazardous Asteroid** is strategically important to NASA and Congress

Asteroid Bennu – One of the Smallest Small Bodies ever Visited

- Bennu is one of the smallest objects ever visited:
  - Mean Diameter = 492 ± 20 meters (1-sigma uncertainty)
  - M = $(7.8 \pm 0.9) \times 10^{10}$ kg (1-sigma uncertainty)
  - GM = μ = 5.2 (3-sigma uncertainty 3.4 to 7.0 m^3/s^2)
- OSIRIS-REx is operating in very close proximity to Bennu, to include contact with the surface:
  - Safe "home" orbit has 1 km radius
- Large *a priori* uncertainty in mass, shape/features, spin axis/rate/pole, albedo and surface properties

Itokawa
535 × 294 × 209 m
$(3.51 \pm 0.105) \times 10^{10}$ kg

Bennu
492 m
$(7.8 \pm 0.9) \times 10^{10}$ kg



Comet 67P
4.1×4.5 km, $(1.0 \pm 0.1) \times 10^{13}$ kg

SPACECRAFT OVERVIEW

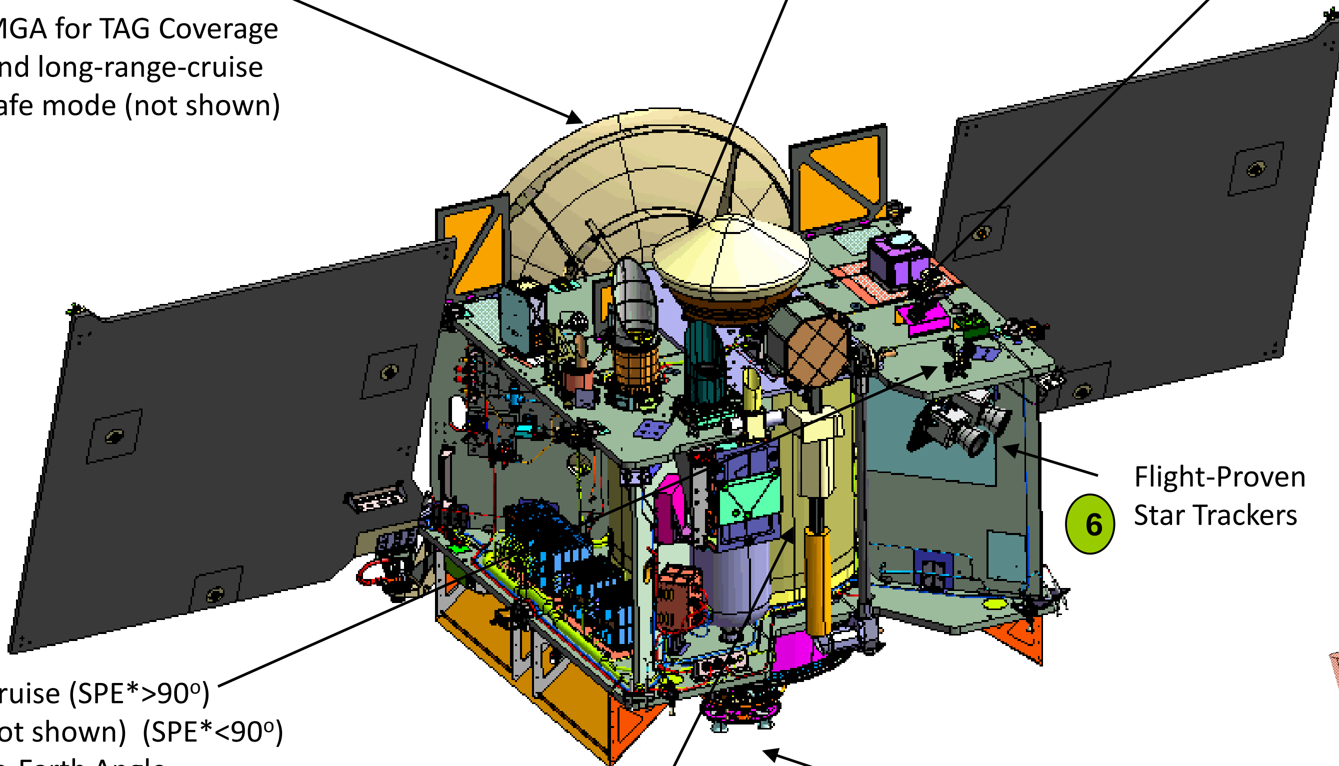
3 Telecom: fixed HGA provides high data rates without gimbaled HGA complexity (& MGA/LGAs)

2 Flight-Proven Stardust-Heritage Sample Return Capsule (SRC)

1 Science Deck

MGA for TAG Coverage and long-range-cruise safe mode (not shown)

2-axis gimbaled Solar Arrays

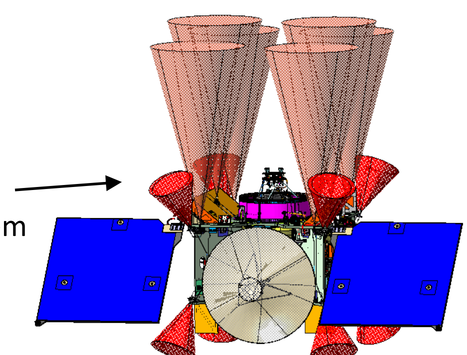


6 Flight-Proven Star Trackers

-X LGA for inner cruise (SPE*>90º)
+X LGA Farside (not shown) (SPE*<90º)
* SPE = Sun-Probe-Earth Angle

4 Single plane of motion TAGSAM w/potentiometers provides simple & reliable positioning

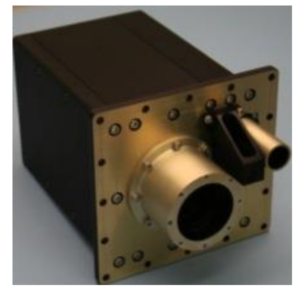
5 High Heritage Propulsion System



Navigation Sensors

- **NavCam (MSSS)**
  - Primary wide-angle navigation camera
- **GN&C Flash Lidar (ASC)**
- PolyCam (University of Arizona)
  - POLYCAM acquires Bennu from 2M km range and refines its ephemeris, performs hi-res survey
  - Primary camera for imaging asteroid and field stars on approach
- MapCam (University of Arizona)
  - MAPCAM performs filter photometry and maps the surface
  - Primary camera for landmark tracking during survey
- OLA Science Lidar (MDA)

NavCam



GN&C LIDAR

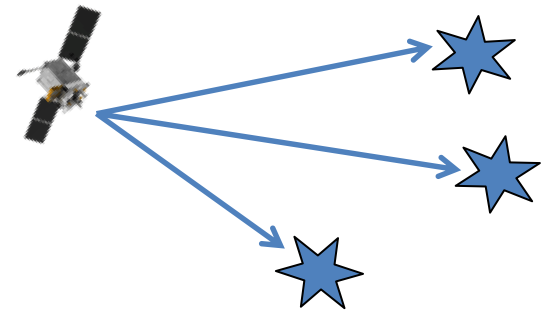
PolyCam

MapCam

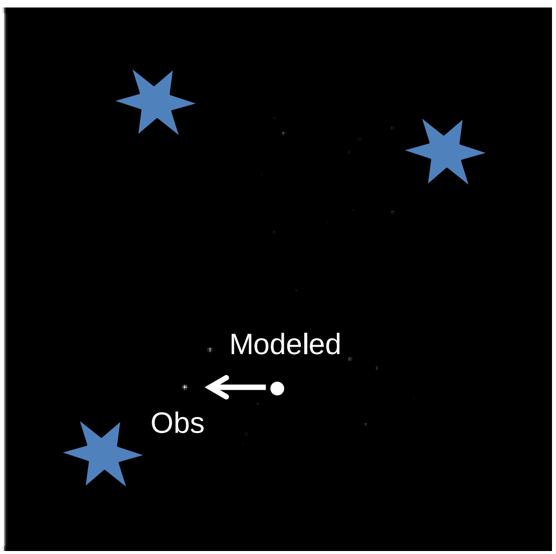
OLA Scanning Lidar

Optical Navigation Phases
Star-based to Landmarks

- Optical Navigation images are needed to determine spacecraft state errors to the required level of accuracy
- Differences between observed and modeled positions of target objects are used to update the spacecraft position & camera pointing

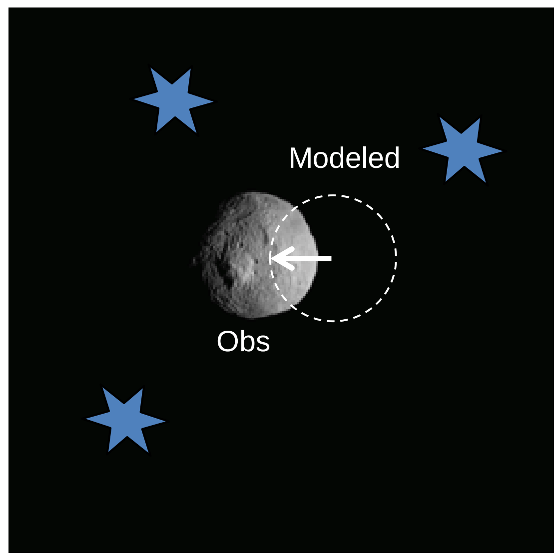


Approach



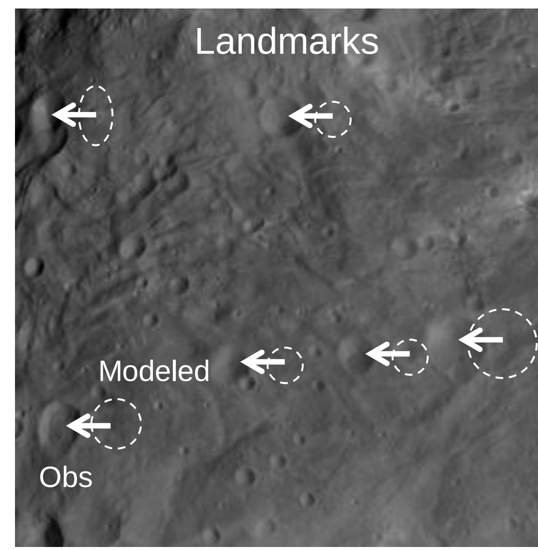
Target body is unresolved and appears against a background of stars

Transition



Target body is partially/fully resolved, stars are still visible

Proximity Ops

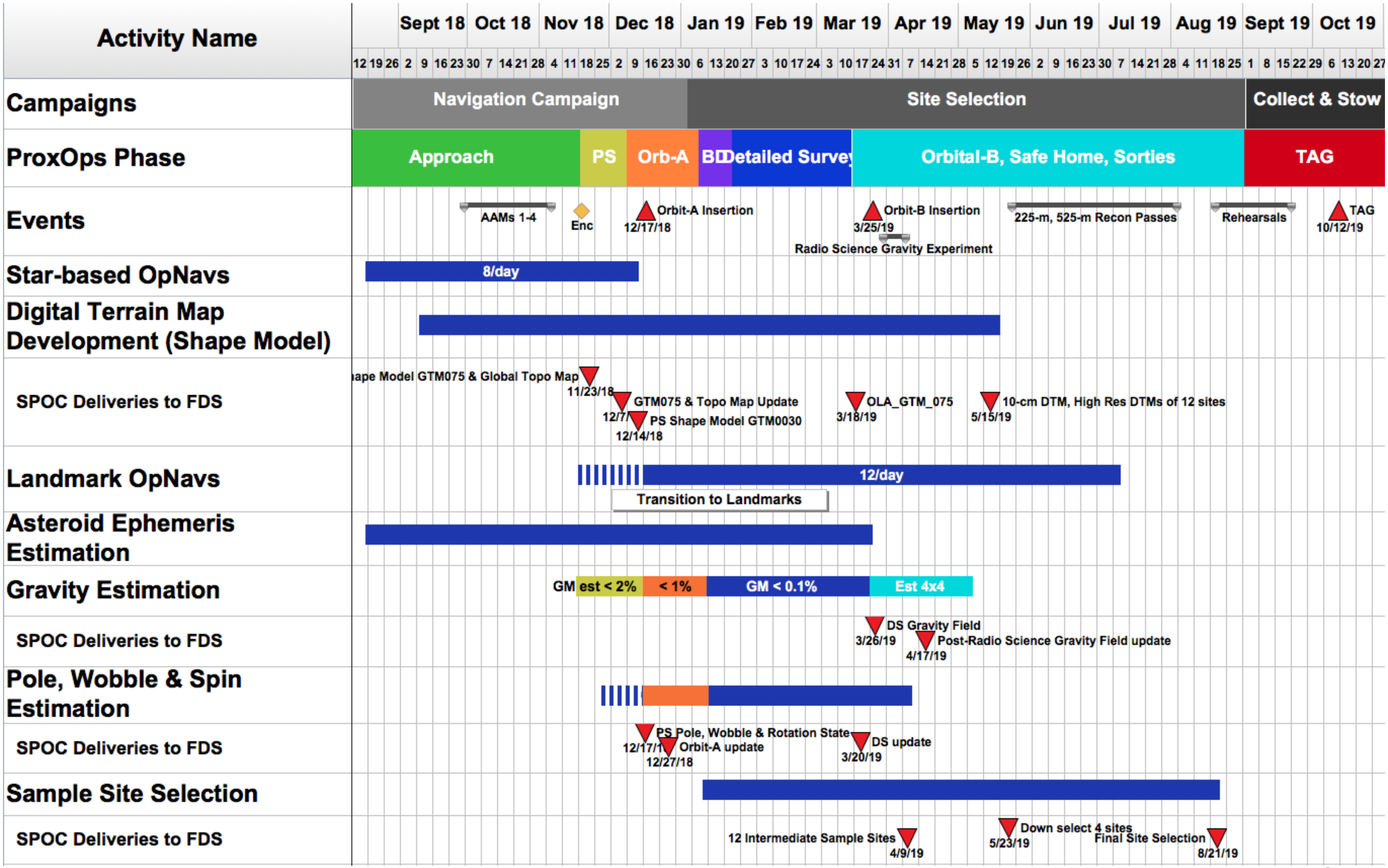


Target body surface fills the entire FOV, no stars or limbs visible

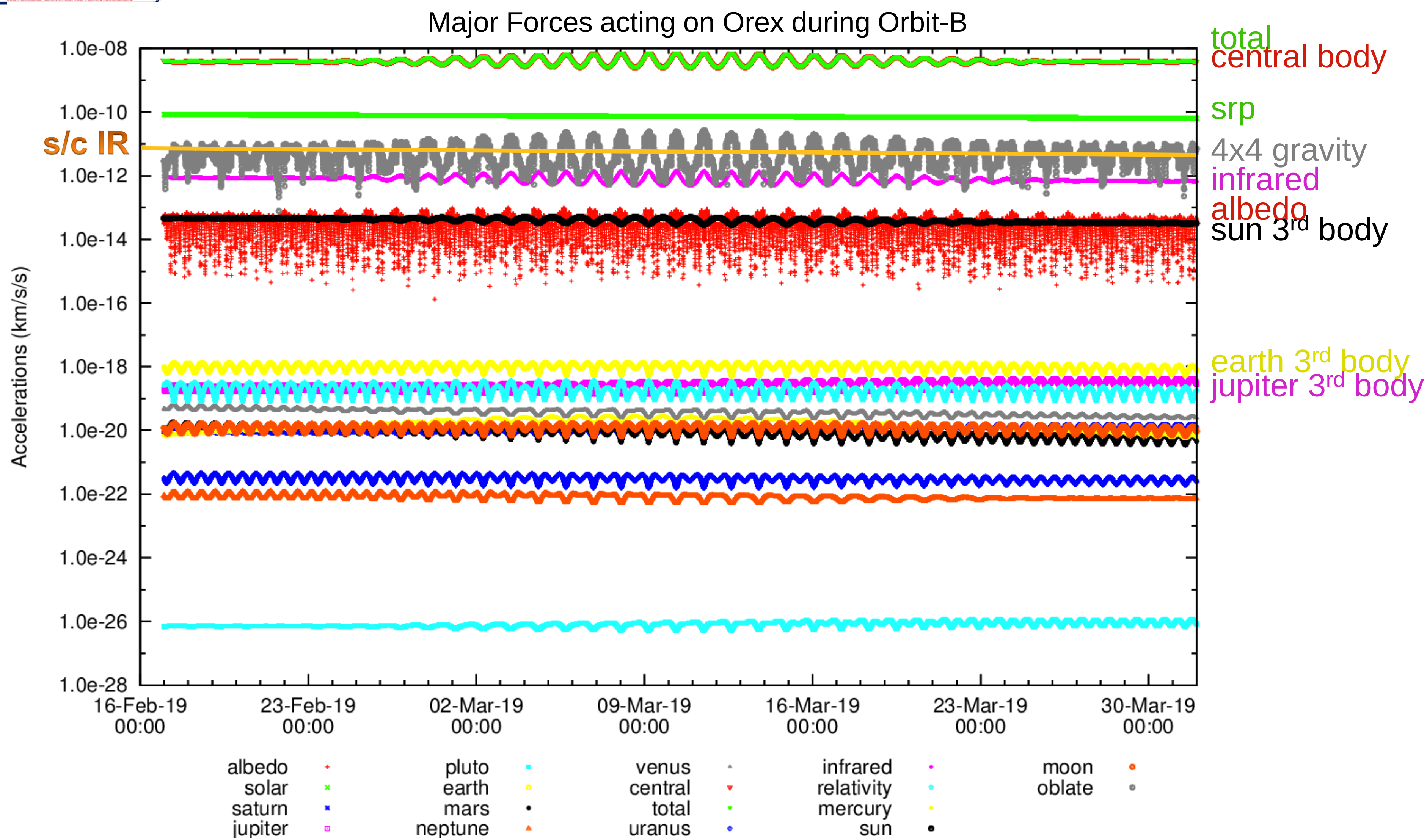
Challenges for Small Body Navigation

- Small perturbations result in large predictive errors in the S/C trajectory down-track position over relatively short periods
  - Small non-gravitational forces 1–10 nm/s^2
    - From solar radiation pressure mis-modeling, S/C thermal radiation, asteroid IR and albedo
  - Small ΔV's momentum desaturation maneuvers are a significant orbital perturbation
    - FDS analysis assumes residual ΔV from a desat is:
      - < 0.5 mm/s (1σ) every 3 days (CBE < 0.1 mm/s (1σ))
      - or < 2 mm/s (1σ) every 10 days
- Science observations, maneuver designs require 10's of meters position accuracy
  - Navigation prediction errors are large relative to orbital radius
  - Requires precise characterization of the small forces to levels less than past planetary or small body missions
  - Also requires frequent late-update OD deliveries to support the rapid pace of maneuvers and observations
- TAG sequence requires down-track errors < 30 m (1σ)
  - This requires non-grav forces to be determined ≤ 3 nm/s^2
    - Assuming a late-update OD with a data cutoff of 24 hrs before Orbit departure

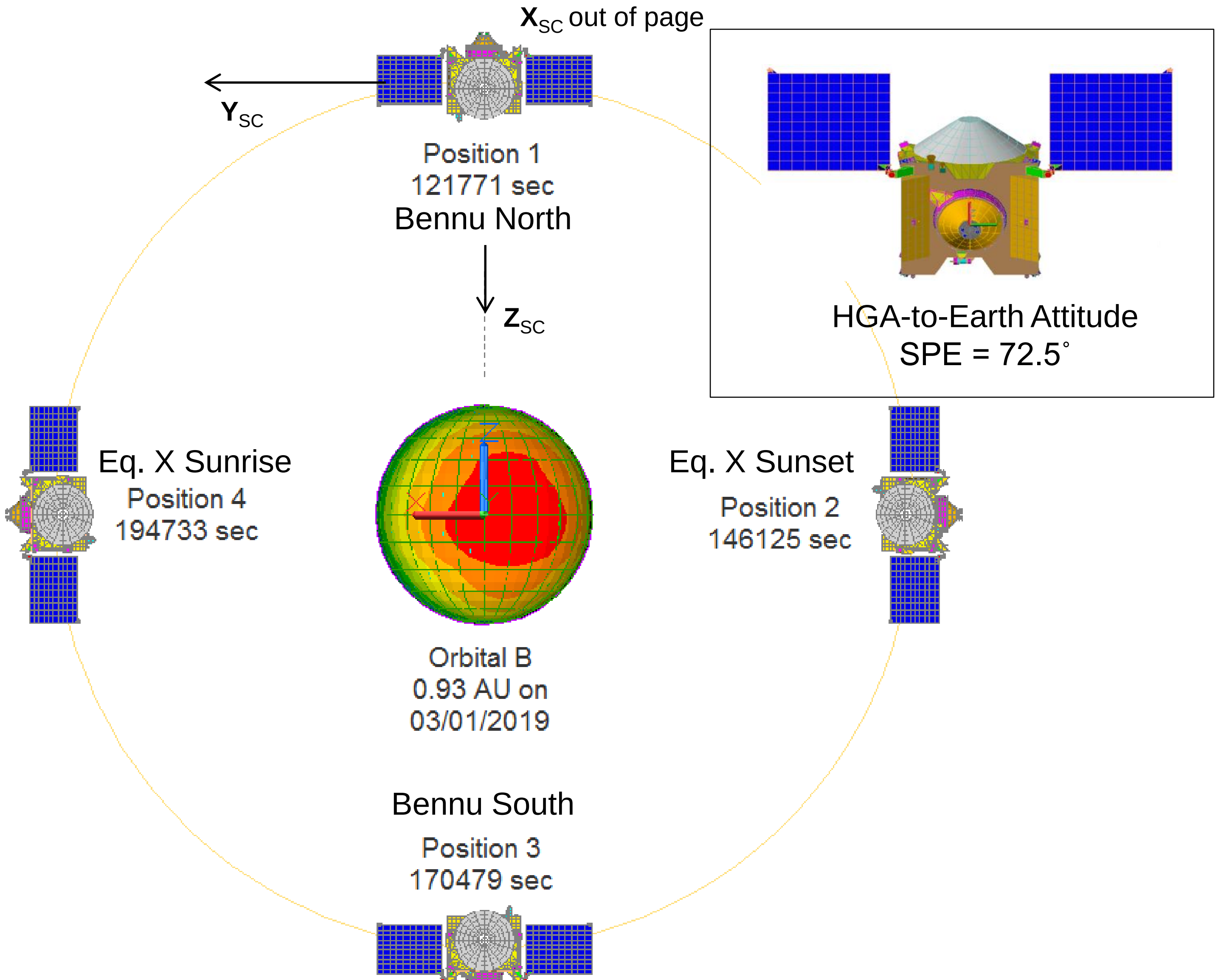
ProxOps Timeline At Bennu and Science Team Deliveries to FDS



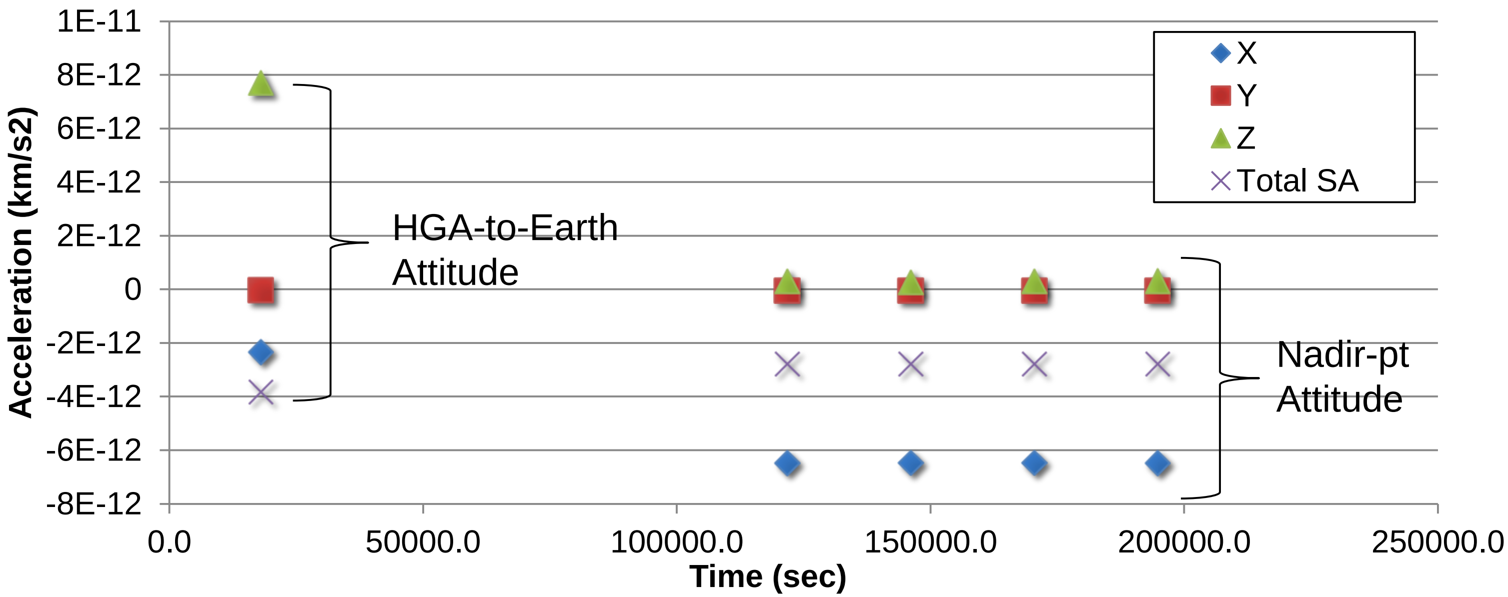
MAJOR FORCES IN 1-KM ORBIT



Thermal Model Orbital Positions



Spacecraft IR Forces



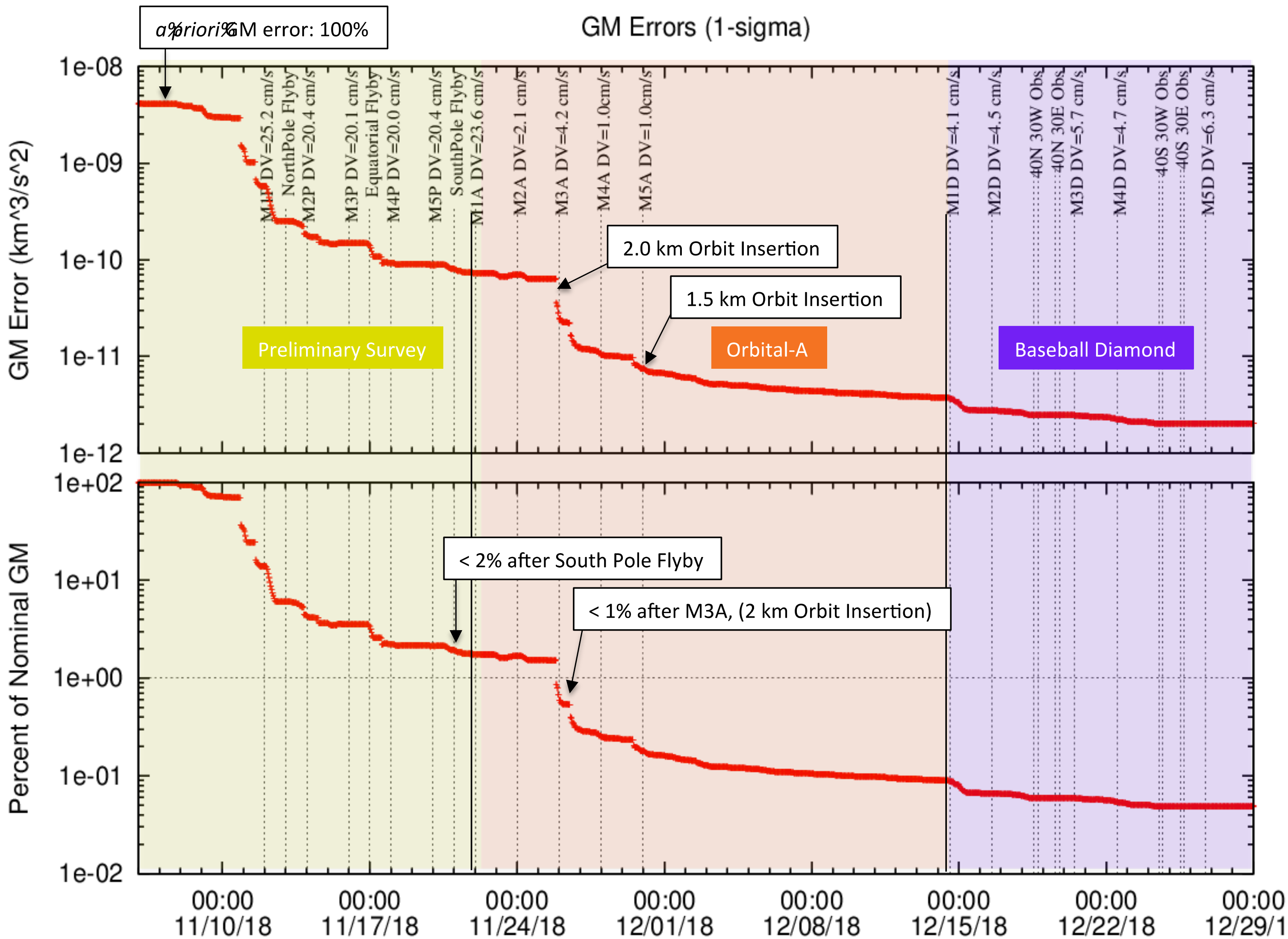
Thermal Model	Solar Dist (AU)	Attitude	Along Each S/C Axis (Face only) X (nm/s^2)	Y (nm/s^2)	Z (nm/s^2)	Solar Arrays (nm/s^2)	Total +X + SA (nm/s^2)	+Z + SA (nm/s^2)	SRP @ AU (nm/s^2)	X/SRP	Z/SRP
Model 1	1.35	Nadir	-2.58	-0.04	-0.02	-0.90	-3.22	-0.80	28	12%	2.9%
		HGA	-1.46	-0.03	2.63	-0.72	-1.97	2.12		7.0%	7.6%
Model 2	0.93	Nadir	-6.47	-0.05	0.31	-2.78	-8.44	-1.65	65	13%	3%
		HGA	-2.33	-0.03	7.71	-3.83	-5.04	5.00		7.7%	7.7%

* HGA Attitude: HGA (+X) at Earth, Sun in X-Z plane

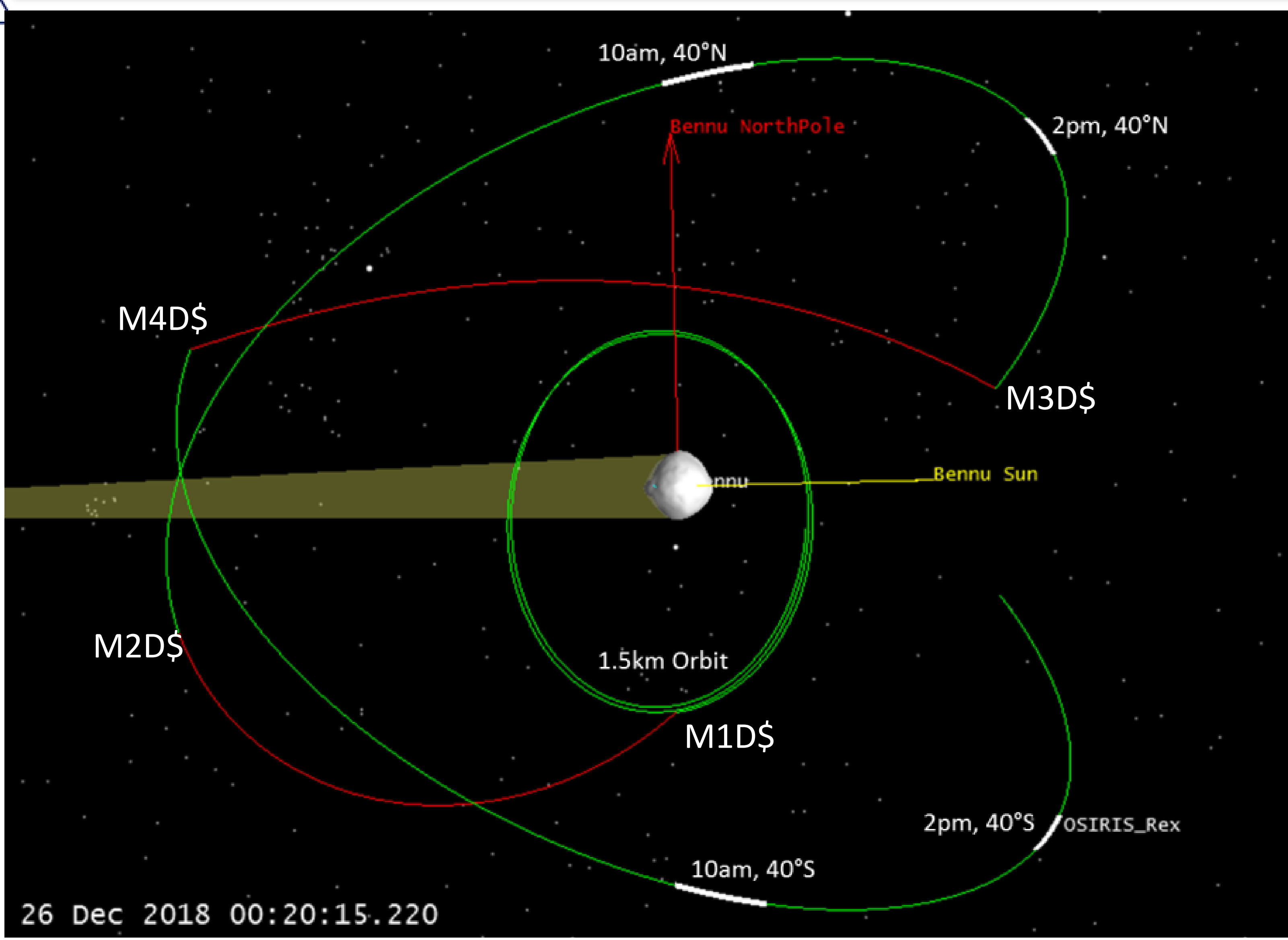
ProxOps Filter Strategy

- Significant Filter Estimated Parameters
  - S/C epoch state
  - Solar Pressure
  - Bennu ephemeris, pole, prime meridian, spin, GM, 4x4 gravity field
  - 3-axis Stochastic non-grav. acceleration to account for small forces
    - (S/C IR, asteroid IR, albedo, SRP)(1-day batches, white noise)
  - Stochastic image pointing errors
    - (batched per image, white noise)
  - Maneuvers (direction, ΔV magnitude)
  - Desat ΔV’s (every 3–10 days)
- Measurements
  - X-band Radio-metric Tracking:
    - 2-way Doppler 8 hrs / day
    - 2-way Range 4 hrs / day
  - Star-based, Landmark OpNavs
    - Star-based: up to 1 / day during Approach through Orbital-A
    - Landmark-based: 8-12 images / day, 1 image every 3–2 hrs
      - Total Landmarks placed equidistant (40 baseline / 100 CBE)

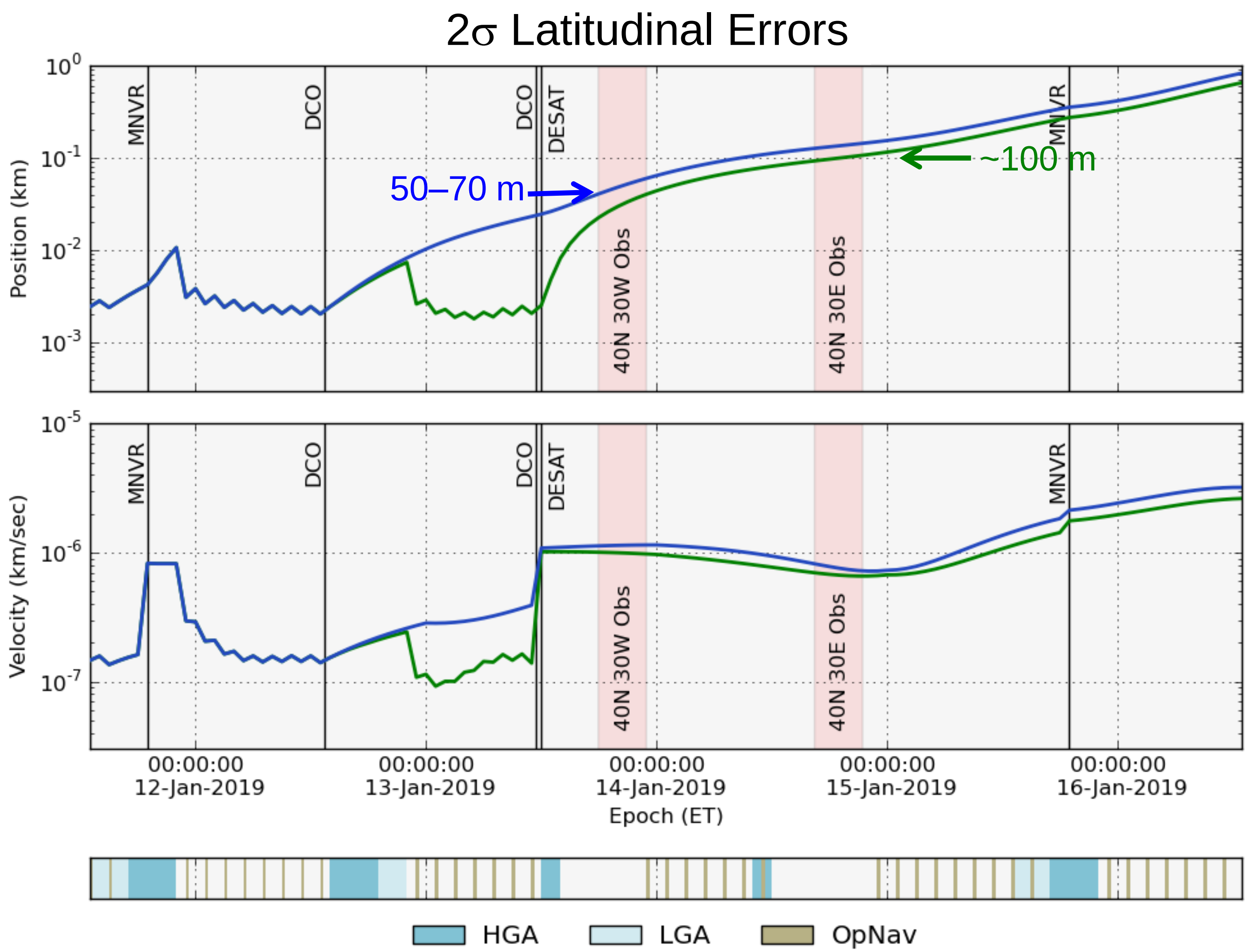
Bennu GM Improvements



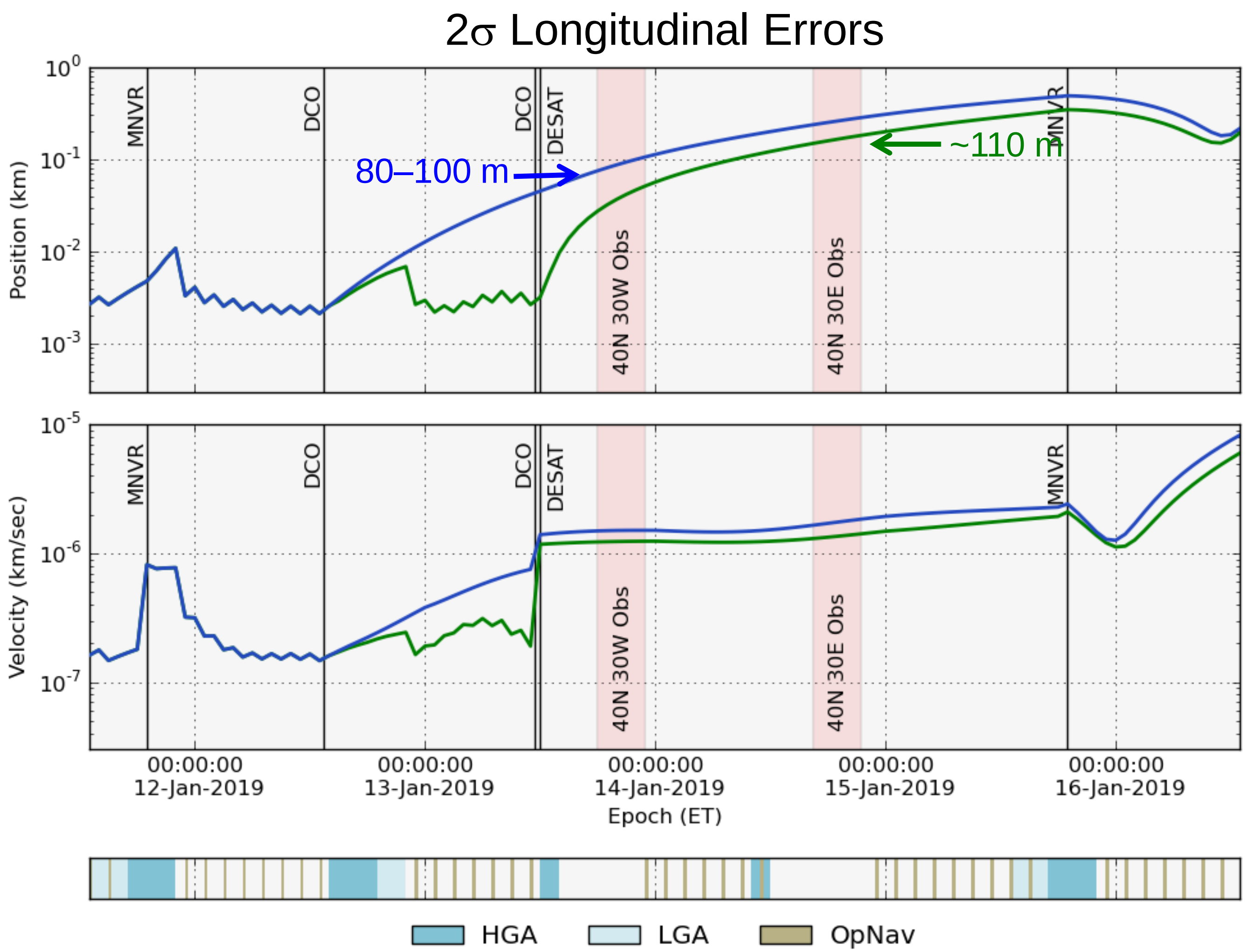
Detailed Survey – Mid-Latitude Observations



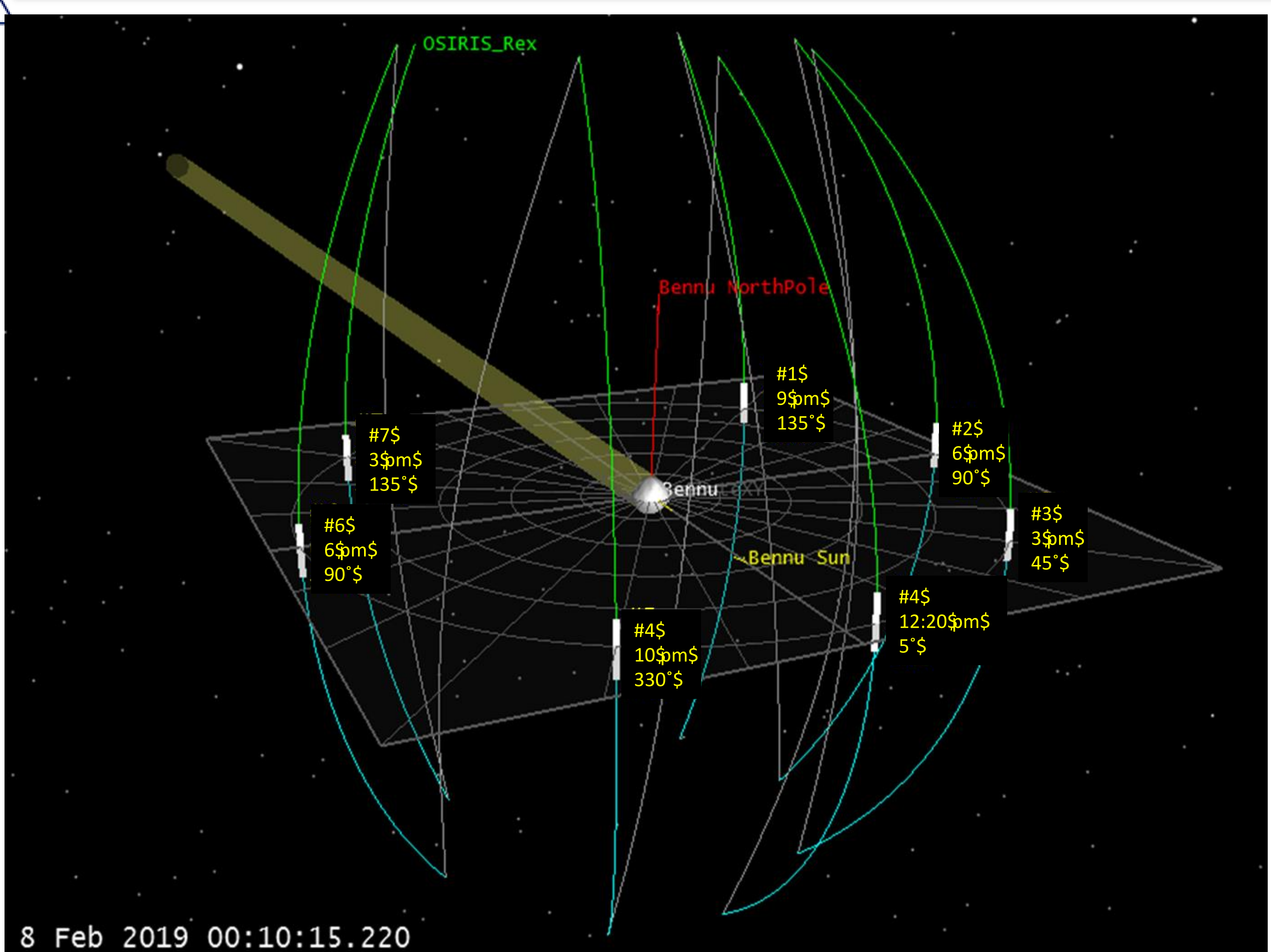
Detailed Survey – Predicted S/C State Errors During Mid-Latitude Observations



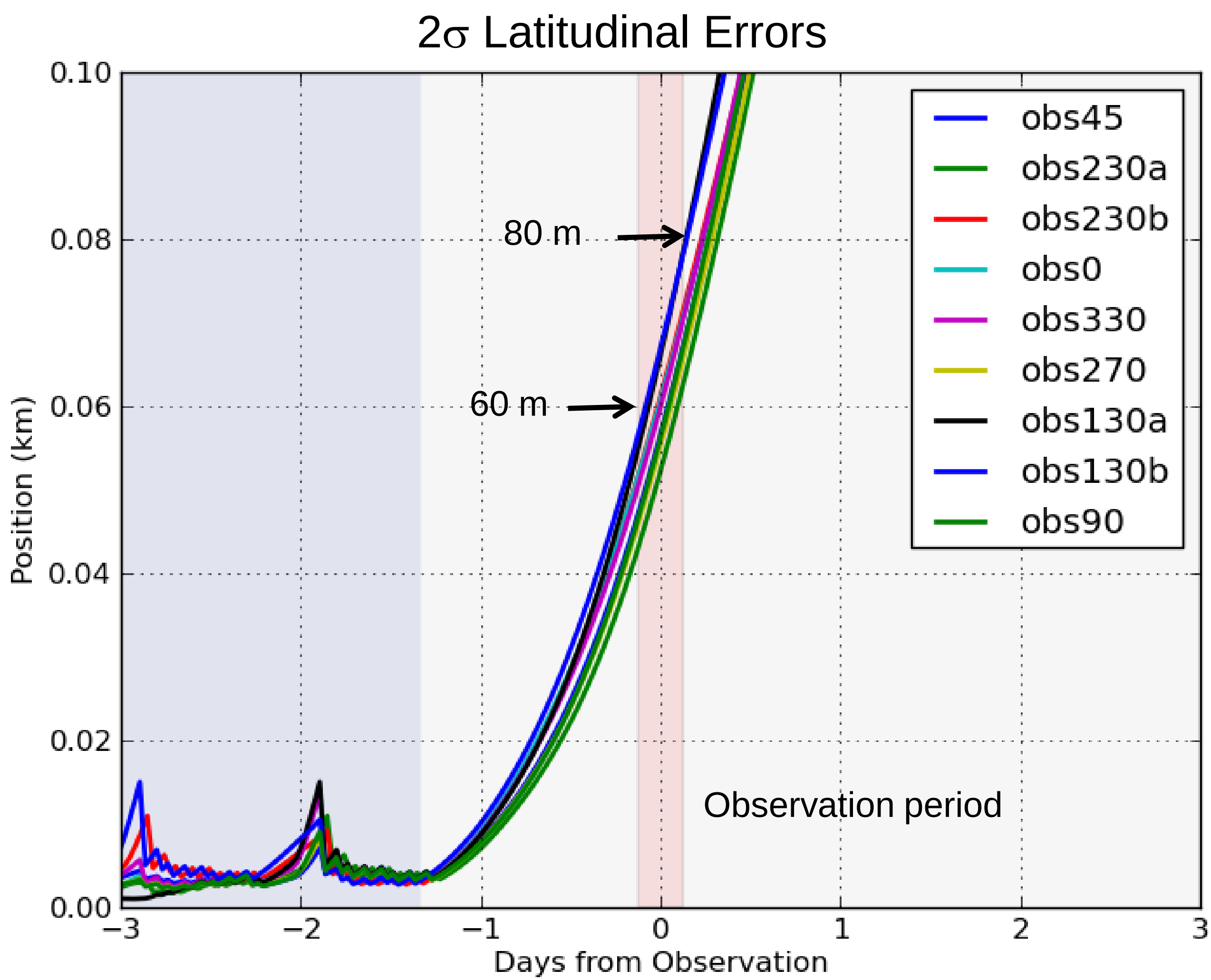
Detailed Survey – Predicted S/C State Errors During Mid-Latitude Observations



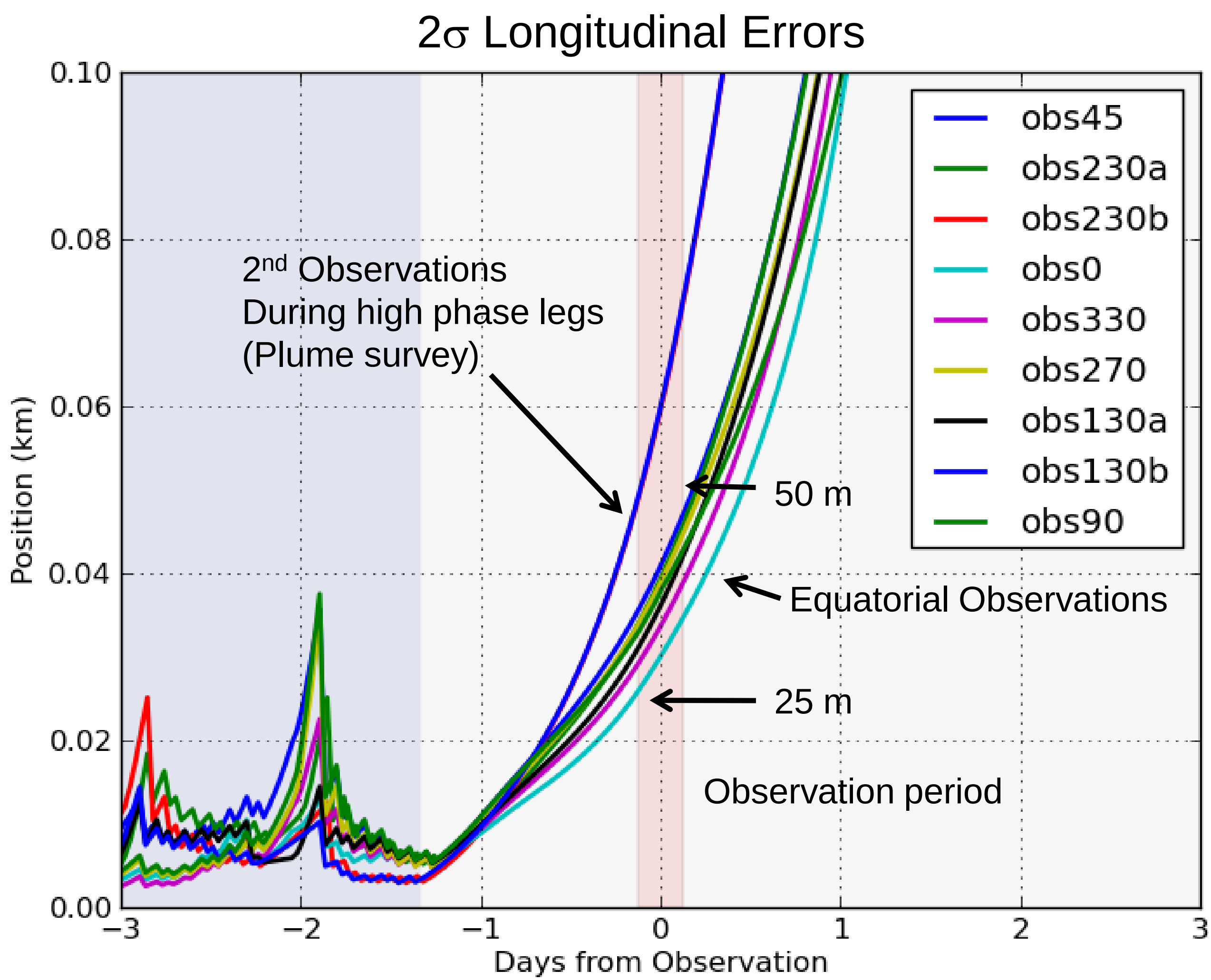
Detailed Survey – Equatorial Observations



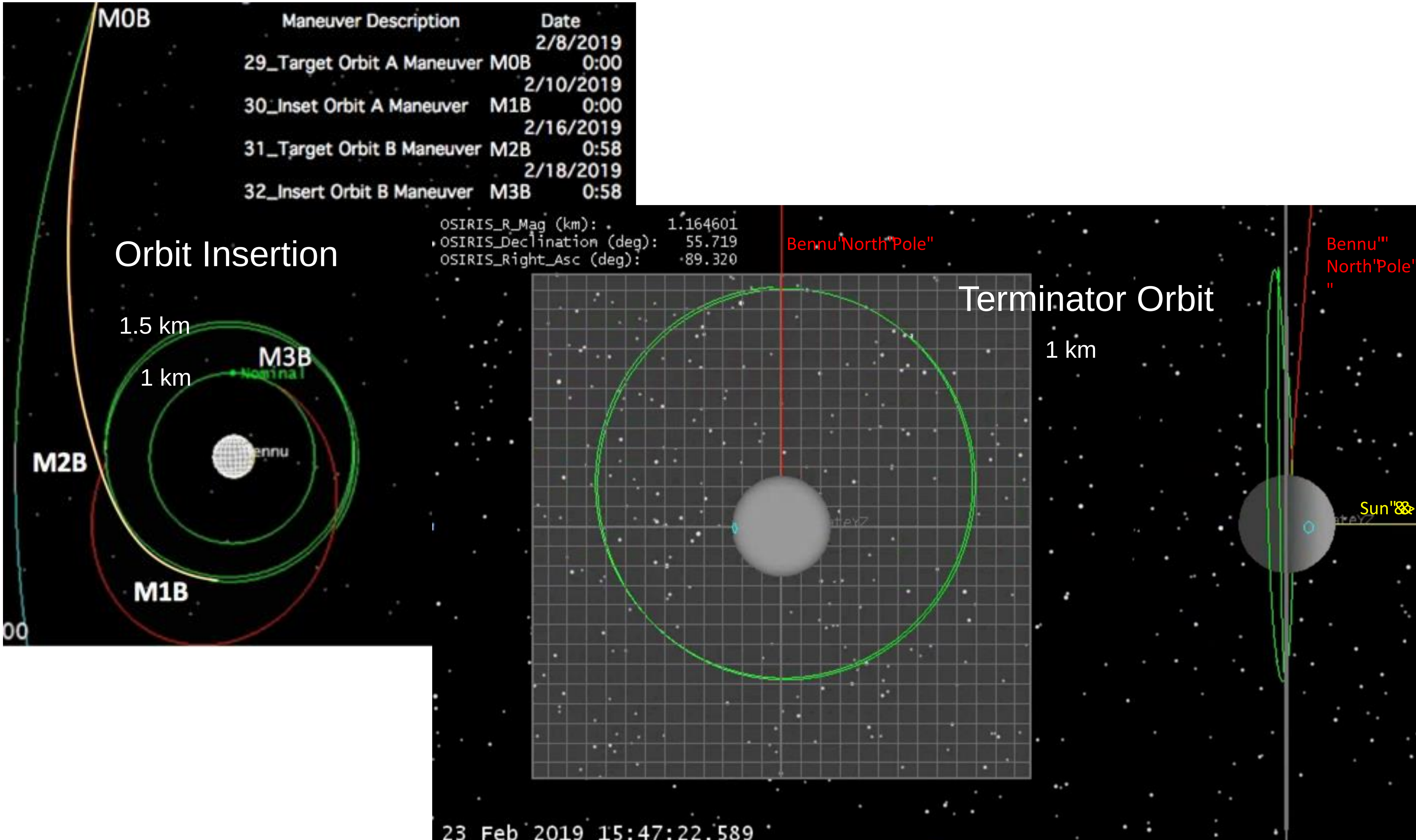
Detailed Survey – Predicted S/C State Errors During Equatorial Observations



DETAILED SURVEY – PREDICTED S/C STATE ERRORS DURING EQUATORIAL OBSERVATIONS

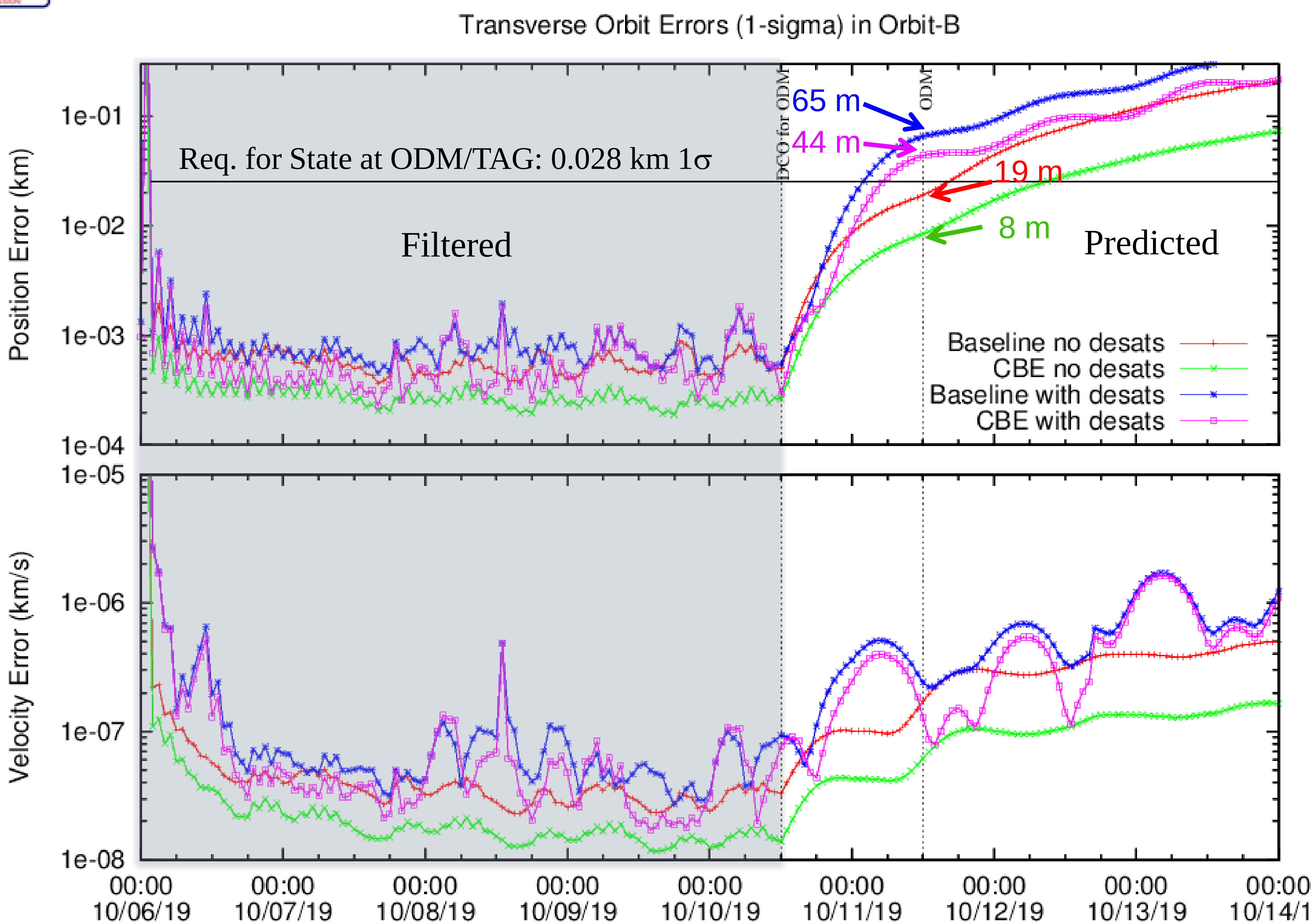


ORBITAL-B



M0B
Maneuver Description
Date
29_Target Orbit A Maneuver M0B 2/8/2019 0:00
30_Inset Orbit A Maneuver M1B 2/10/2019 0:00
31_Target Orbit B Maneuver M2B 2/16/2019 0:58
32_Insert Orbit B Maneuver M3B 2/18/2019 0:58
Orbit Insertion
1.5 km
1 km
M3B
Nominal
M2B
M1B
OSIRIS_R_Mag (km): 1.164601
OSIRIS_Declination (deg): 55.719
OSIRIS_Right_Asc (deg): 89.320
Bennu North Pole
Terminator Orbit
1 km
Sun
23 Feb 2019 15:47:22.589

ORBITAL-B – PREDICTED S/C TRANSVERSE ERRORS



Orbital-B – Predicted S/C State Errors† (1σ) No Desats

No Desat Errors in Predictions

Case	Desats in predict	Map Time	R (m)	T (m)	N (m)	DR (mm/s)	DT (mm/s)	DN (mm/s)	Downtrack Timing Error	Downtrack Pt Error (deg)	Crosstrack Pt Error (deg)
At DCO										using mean motion*time	
Baseline	None	10-Oct-19 12:00	0.77	**0.50**	0.59	0.07	0.03	0.01	.1 min	0.0	0.0
CBE	None	10-Oct-19 12:00	0.37	**0.26**	0.18	0.03	0.01	0.00	.1 min	0.0	0.0
Predict 1 day											
Baseline	None	11-Oct-19 12:00	4.22	**19.15**	1.28	1.42	0.17	0.01	4.4 min	1.1	0.1
CBE	None	11-Oct-19 12:00	1.56	**8.48**	1.26	0.62	0.06	0.01	2. min	0.5	0.1
Predict 2 days											
Baseline	None	12-Oct-19 12:00	8.27	**77.97**	1.29	5.64	0.31	0.04	18. min	4.5	0.1
CBE	None	12-Oct-19 12:00	2.84	**28.49**	1.27	2.06	0.11	0.01	6.6 min	1.6	0.1
Predict 1 week											
Baseline	None	17-Oct-19 12:00	12.99	**656.39**	1.26	47.38	0.70	0.30	2.53 hr	37.6	0.1
CBE	None	17-Oct-19 12:00	4.31	**222.73**	1.23	16.08	0.23	0.10	.86 hr	12.8	0.1
Predict 2 weeks											
Baseline	None	24-Oct-19 12:00	59.82	**1982.51**	2.98	146.60	0.97	0.93	7.64 hr	113.6	0.2
CBE	None	24-Oct-19 12:00	20.07	**666.15**	1.33	49.27	0.34	0.31	2.57 hr	38.2	0.1
Predict 4 weeks											
Baseline	None	7-Nov-19 12:00	335.41	**6775.91**	15.86	600.60	1.37	3.85	26.1 hr	388.2	0.9
CBE	None	7-Nov-19 12:00	112.52	**2267.19**	2.96	201.00	0.64	1.45	8.73 hr	129.9	0.2

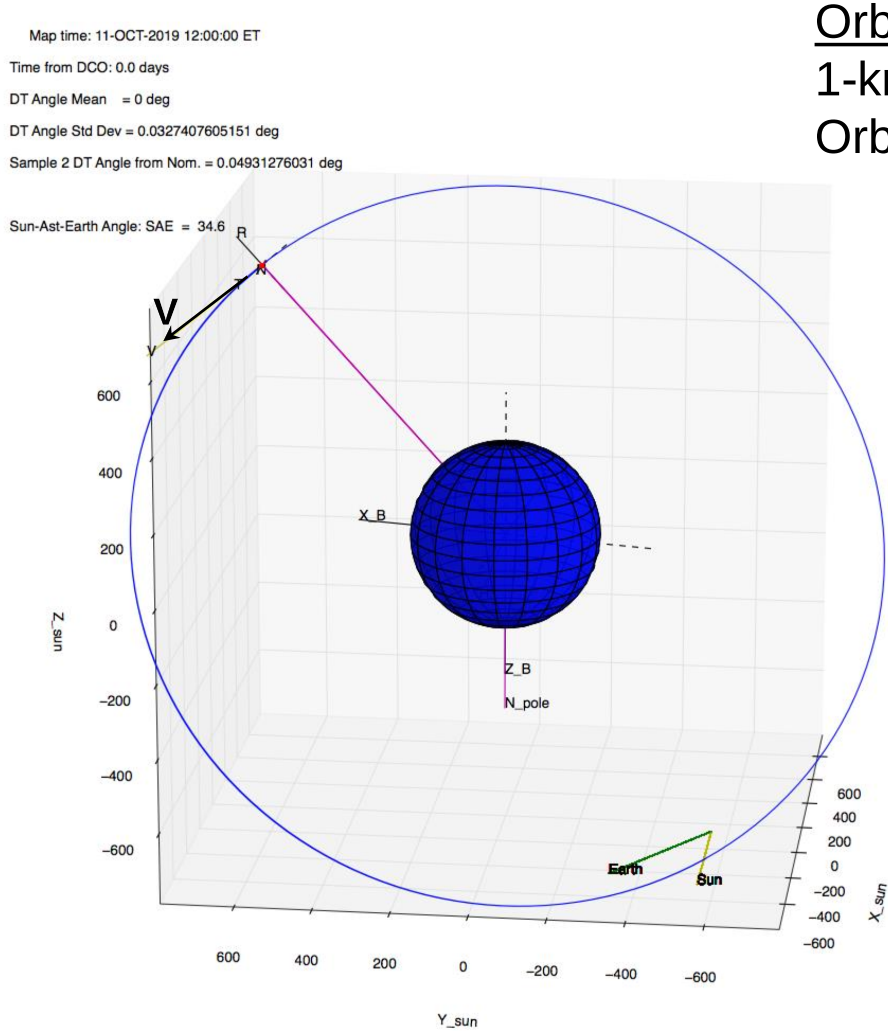
†Assumes T error maps directly into down-track timing, true anomaly or pointing error of circular orbit

Orbital-B – Predicted S/C State Errors† (1σ) With 3-day Desats

Case	Desats in predict	Map Time	R (m)	T (m)	N (m)	DR (mm/s)	DT (mm/s)	DN (mm/s)	Downtrack Timing Error	Downtrack Pt Error (deg)	Crosstrack Pt Error (deg)
At DCO										using mean motion*time	
Baseline	Desats	10-Oct-19 12:00	0.64	**0.55**	0.38	0.06	0.09	0.04	.1 min	0.0	0.0
CBE	Desats	10-Oct-19 12:00	0.46	**0.29**	0.31	0.03	0.08	0.03	.1 min	0.0	0.0
Predict 1 day											
Baseline	Desats	11-Oct-19 12:00	7.14	**65.34**	1.92	4.50	0.24	0.02	15.1 min	3.7	0.1
CBE	Desats	11-Oct-19 12:00	3.97	**43.58**	3.65	2.92	0.13	0.02	10.1 min	2.5	0.2
Predict 2 days											
Baseline	Desats	12-Oct-19 12:00	9.87	**156.30**	1.77	10.95	0.34	0.05	36.1 min	9.0	0.1
CBE	Desats	12-Oct-19 12:00	4.43	**97.16**	3.50	6.65	0.14	0.03	22.5 min	5.6	0.2
Predict 1 week											
Baseline	Desats	17-Oct-19 12:00	15.44	**1082.00**	7.99	77.13	1.04	0.83	4.17 hr	62.0	0.5
CBE	Desats	17-Oct-19 12:00	9.70	**813.00**	7.50	57.50	0.83	0.75	3.13 hr	46.6	0.4
Predict 2 weeks											
Baseline	Desats	24-Oct-19 12:00	98.09	**2973.00**	18.78	218.90	1.66	1.78	11.45 hr	170.3	1.1
CBE	Desats	24-Oct-19 12:00	75.45	**2204.00**	18.41	161.70	1.74	1.45	8.49 hr	126.3	1.1
Predict 4 weeks											
Baseline	Desats	7-Nov-19 12:00	501.20	**8984.00**	42.47	803.50	4.05	6.05	34.61 hr	514.7	2.4
CBE	Desats	7-Nov-19 12:00	340.60	**6104.00**	43.74	545.70	5.39	6.73	23.51 hr	349.7	2.5

†Assumes T error maps directly into down-track timing, true anomaly or pointing error of circular orbit

DCO+ 1 Day
No Desats

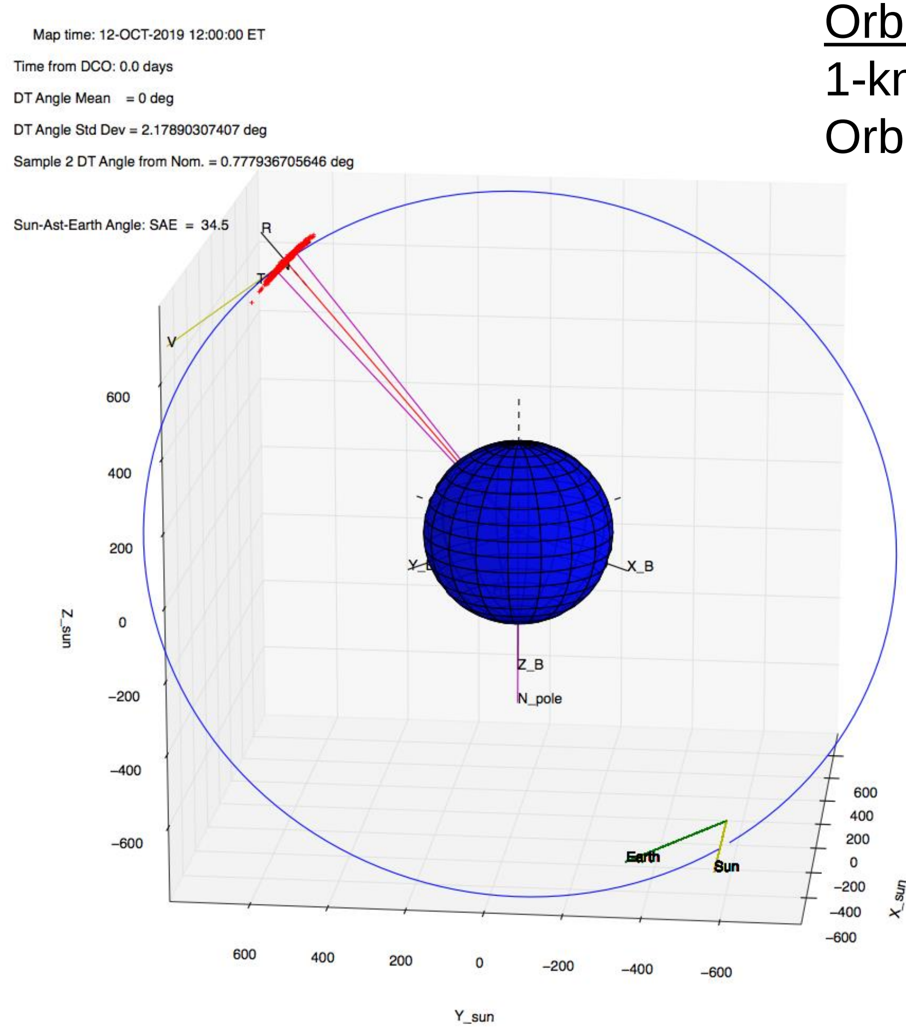


Orbital-B

1-km Orbit

Orbit Period: ~ 24 hrs

DCO+ 2 Days
No Desats

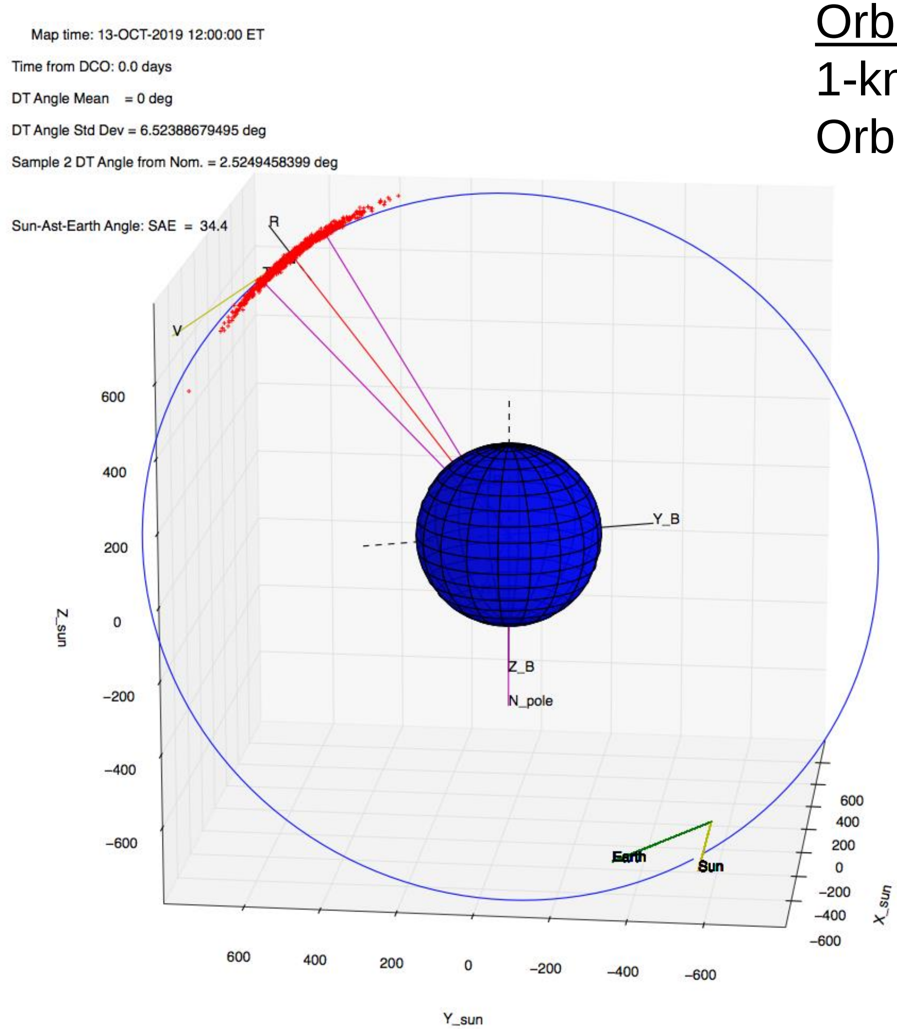


Orbital-B

1-km Orbit

Orbit Period: ~ 24 hrs

DCO + 3 DAYS
No Desats



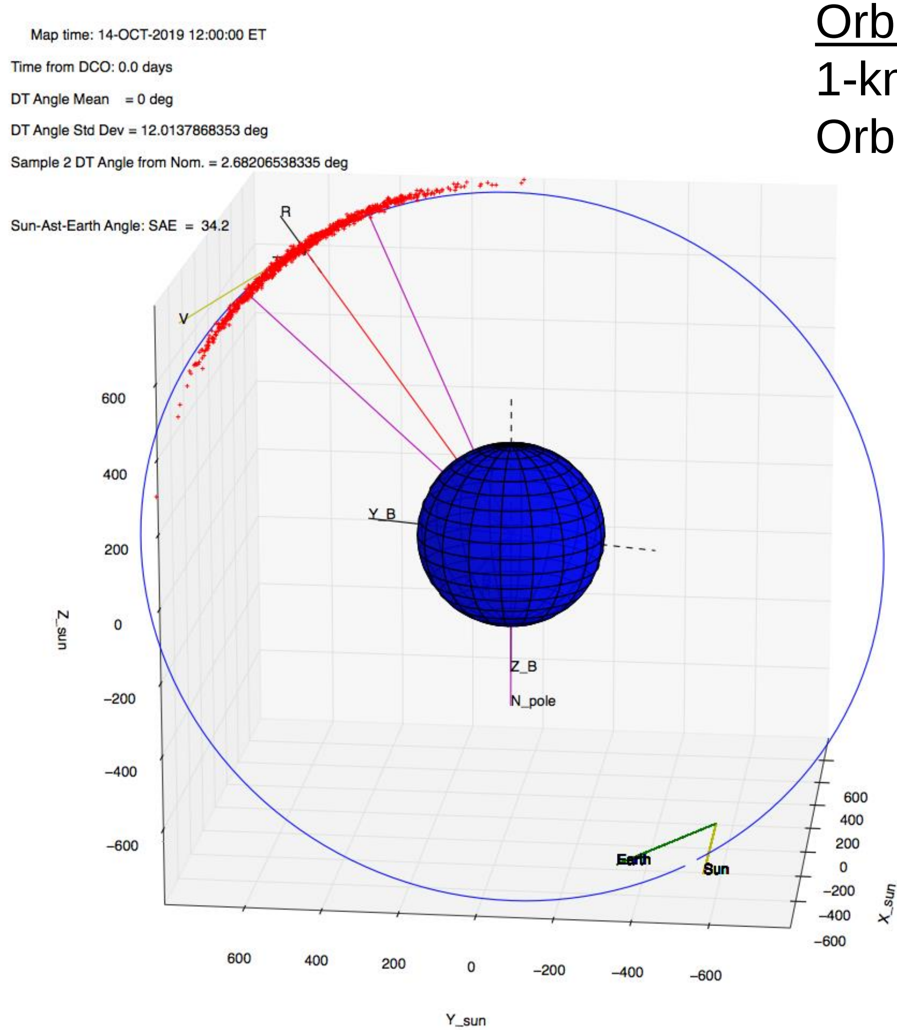
<u>Orbital-B</u>

1-km Orbit

Orbit Period: ~ 24 hrs

DCO+ 4 DAYS

No Desats

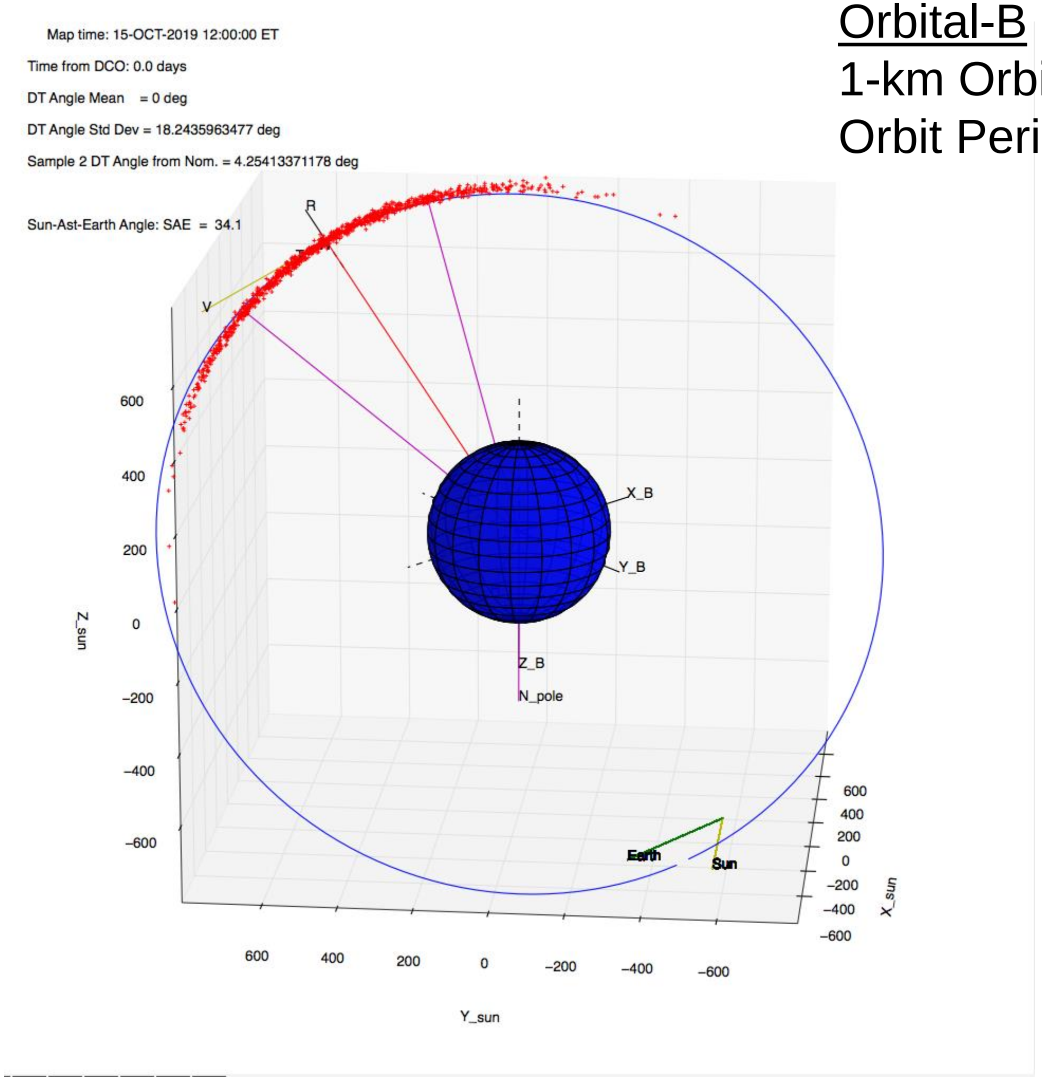


<u>Orbital-B</u>

1-km Orbit

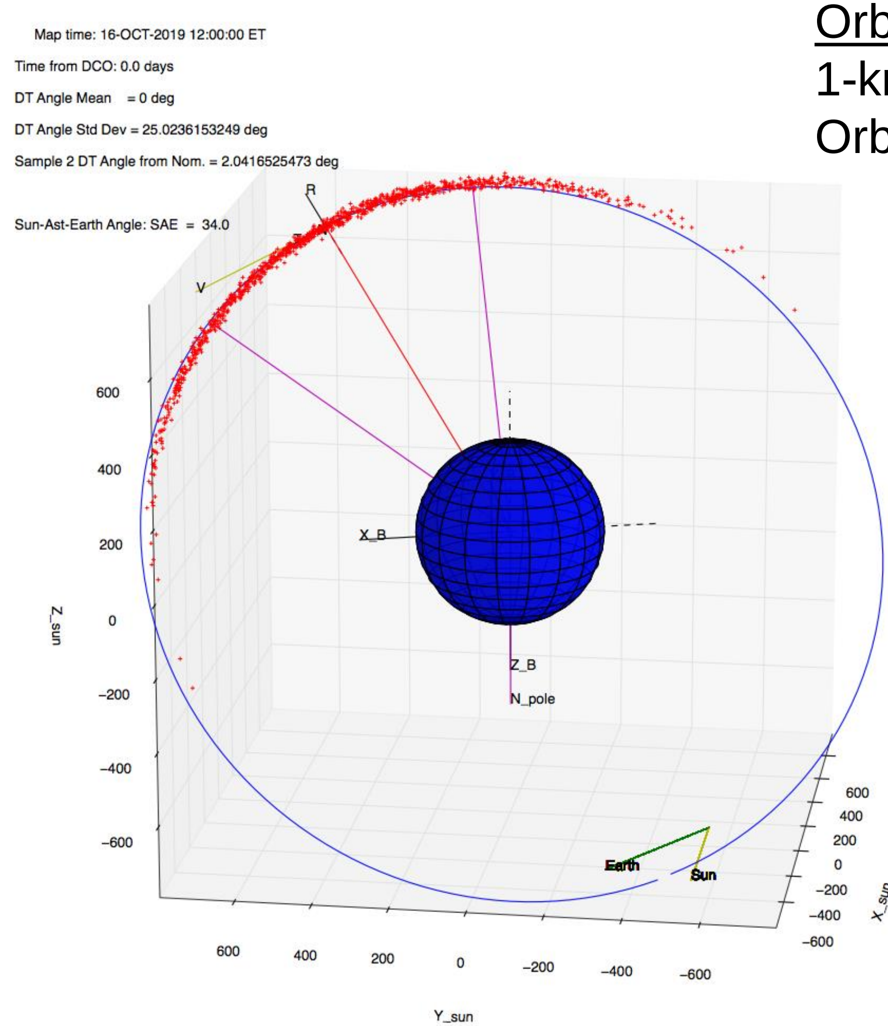
Orbit Period: ~ 24 hrs

DCO+ 5 DAYS
No Desats



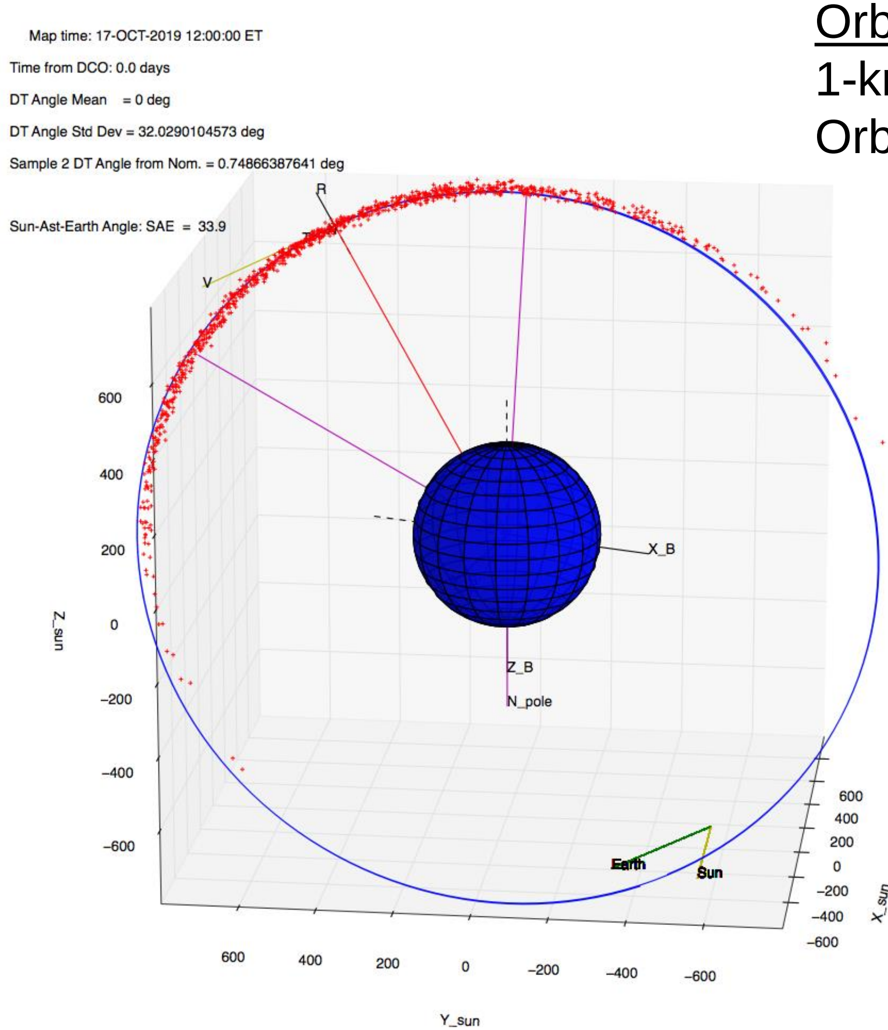
Orbital-B
1-km Orbit
Orbit Period: ~ 24 hrs

DCO+ 6 Days
No Desats



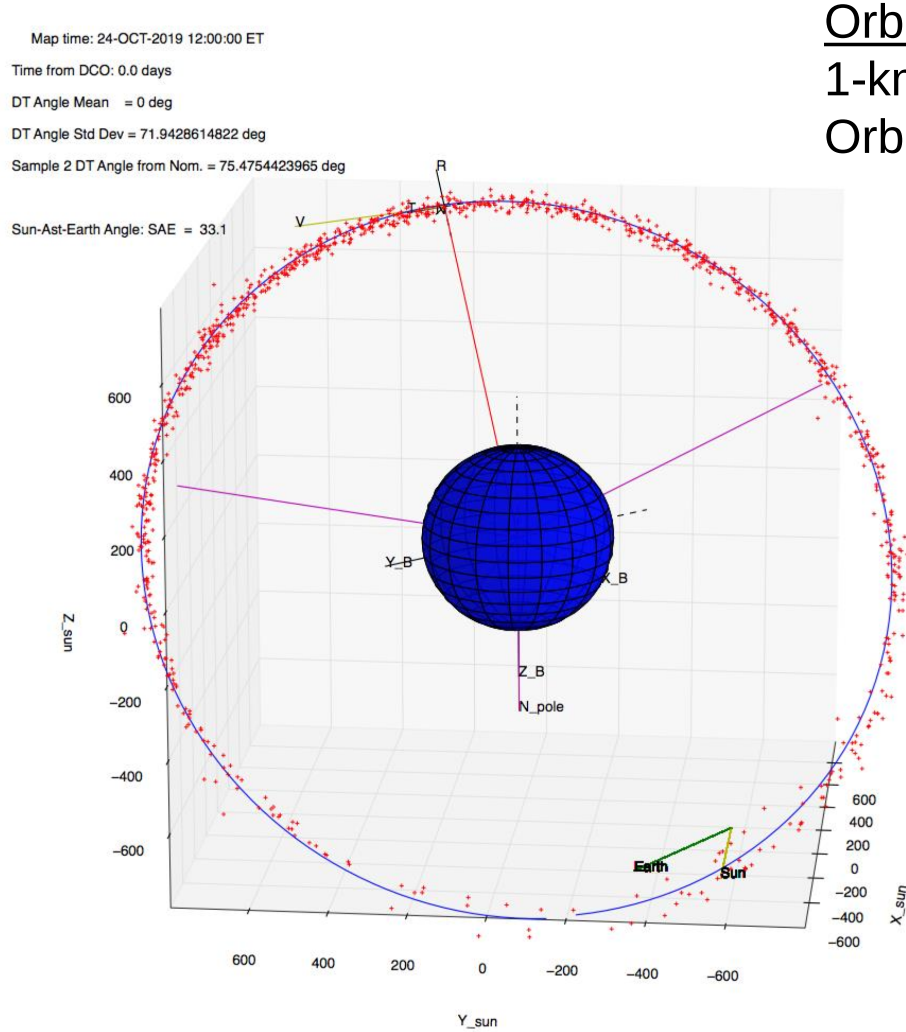
Orbital-B
1-km Orbit
Orbit Period: ~ 24 hrs

DCO+1 WEEK
No Desats



<u>Orbital-B</u>
1-km Orbit
Orbit Period: ~ 24 hrs

DCO+2 WEEKS
No Desats



Orbital-B

1-km Orbit

Orbit Period: ~ 24 hrs

Summary

- OSIRIS-REx mission requires unprecedented levels of navigation performance during Bennu Proximity Operations
  - Science Observations, Orbit insertion, Recon and TAG require predicted state errors to be on the order of 10's of meters
    - This in turn requires late OD deliveries for updating the planned maneuver or Science observation with OpNav images shuttered ~24 hrs before the event
  - Successful TAG requires the non-gravitational forces to be characterized ≤ 3 nm/s^2 level
  - Rapid cadence of maneuvers and observation plans are required to meet Mission & Science Objectives

Backup

OSIRIS-REx

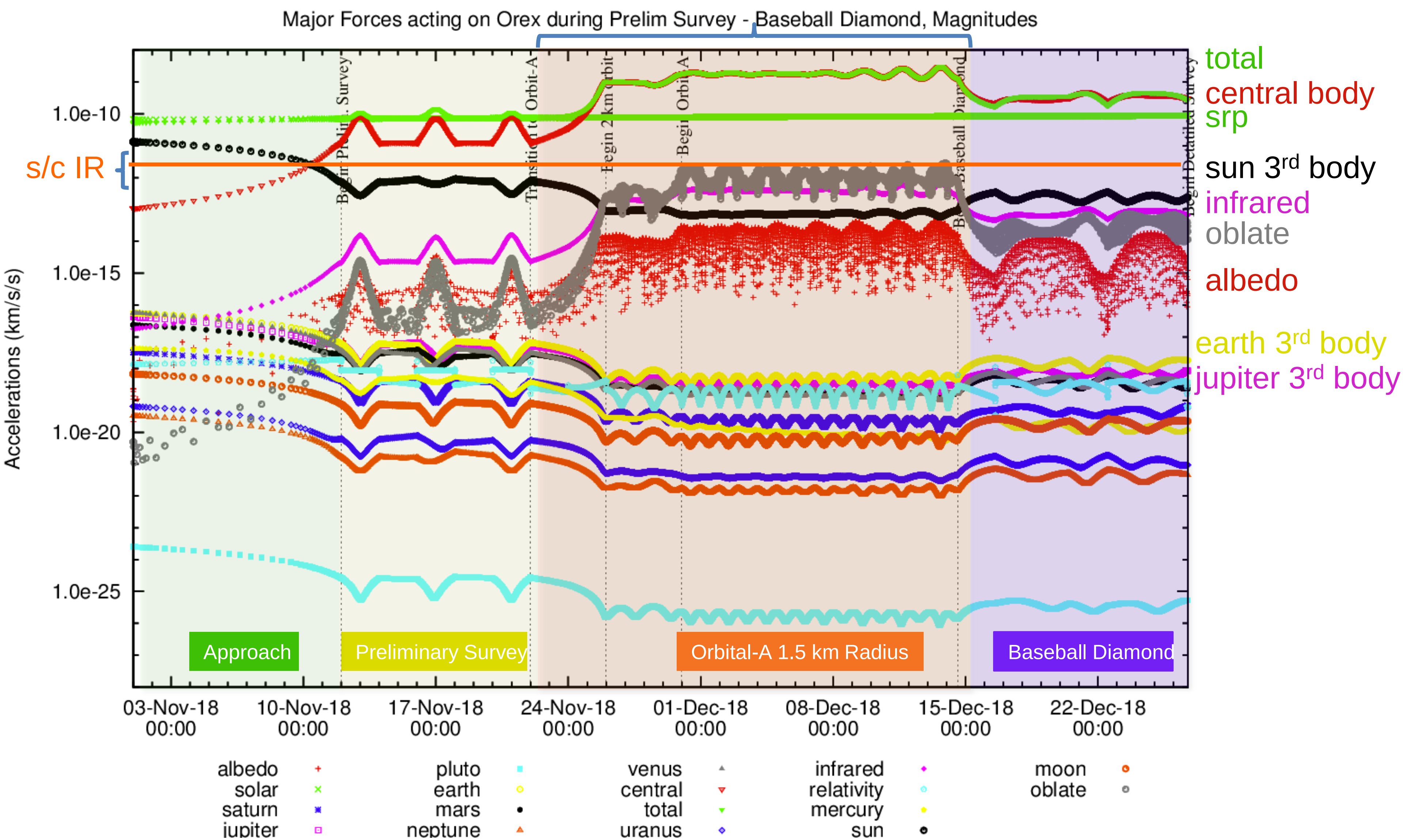
Defined

- **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

Mission Success

- **Rendezvous** with asteroid Bennu
- **Contact** the asteroid surface with TAGSAM and **collect a sample**
- Safely **return** asteroid sample to Earth and deliver them to the curatorial facility at the NASA Johnson Space Center
- Provide for the initial **analysis** and plan for the long-term **curation** of the returned sample
- Ensure a sample allocation process is in place to conduct early **science** return studies as well as long-term general studies

Representative Major Forces
Early Proximity Operations



Two-Year Cruise