



# OSIRIS-REx

ASTEROID SAMPLE RETURN MISSION



## OSIRIS-REx Dancing with Asteroid Bennu

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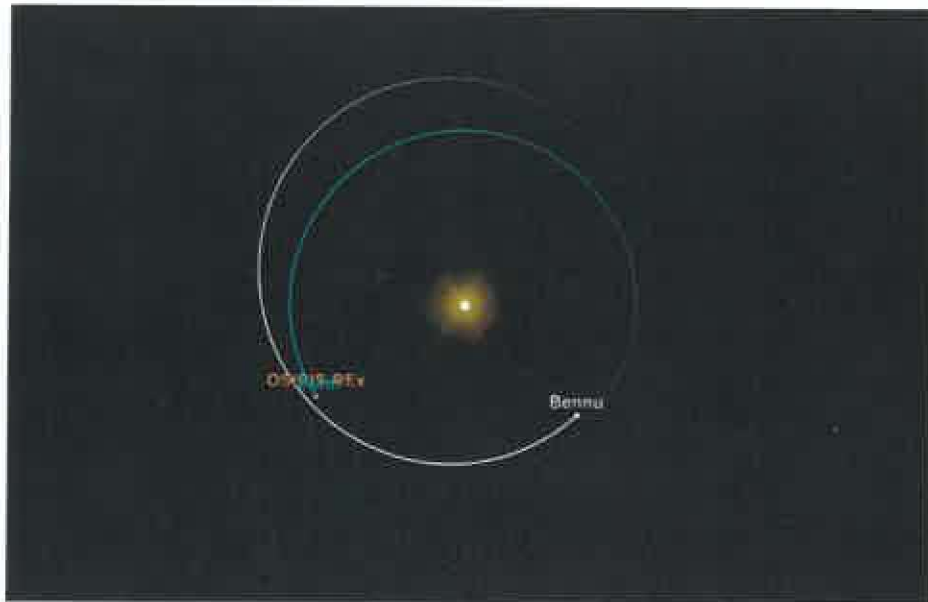
UNIVERSITY OF ARIZONA

NASA'S GODDARD SPACE FLIGHT CENTER

LOCKHEED MARTIN



# OSIRIS-REx Overview



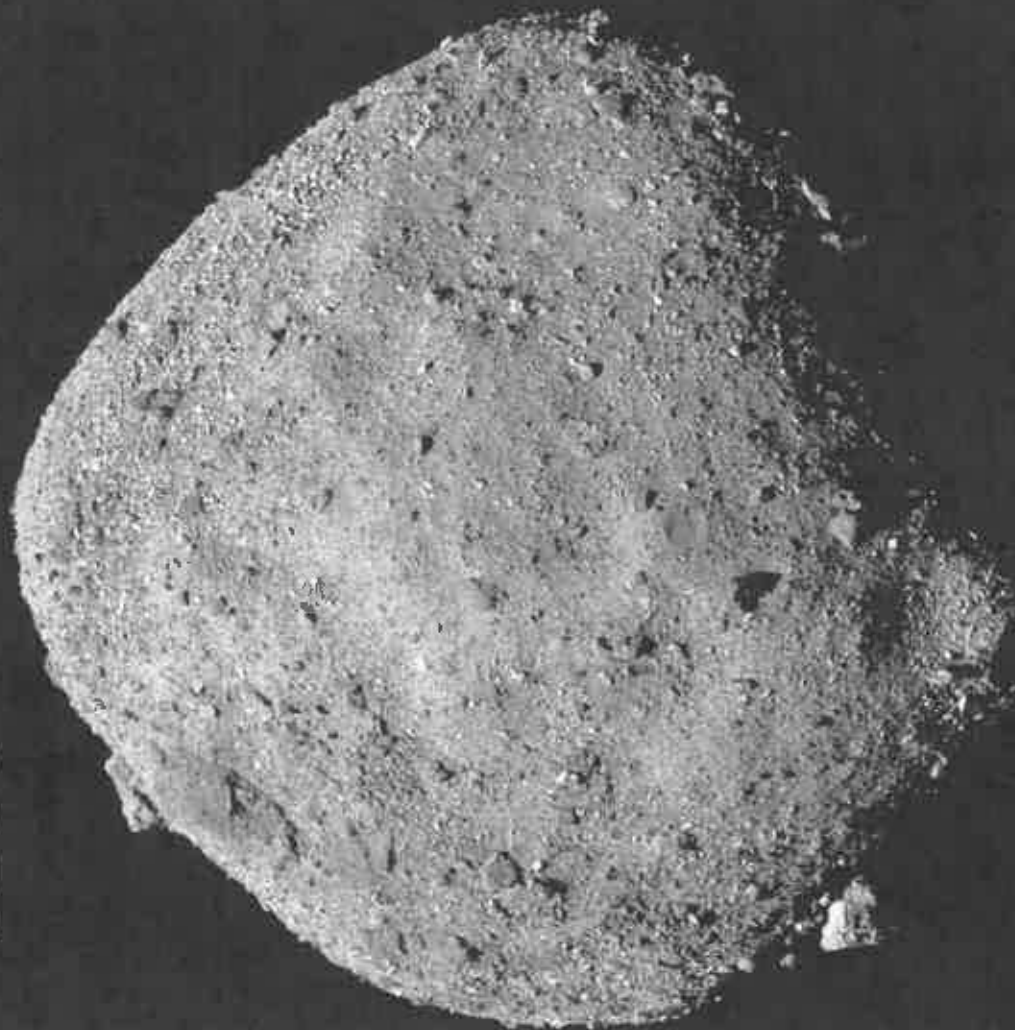
- **Origins**
  - Return and analyze a sample of pristine carbonaceous asteroid regolith
- **Spectral Interpretation**
  - Provide ground truth for telescopic data of the entire asteroid population
- **Resource Identification**
  - Map the chemistry and mineralogy of a primitive carbonaceous asteroid
- **Security**
  - Measure the Yarkovsky effect on a potentially hazardous asteroid
- **Regolith Explorer**
  - Document the regolith at the sampling site at scales down to the sub-cm

## OSIRIS-REx MISSION OPERATIONS TIMELINE



# Asteroid 101955 Bennu – Prior to Arrival





Full rotation PolyCam  
mosaic from Approach  
~0.5 meter/pixel resolution  
~50 deg phase





# How Tall is Asteroid Bennu?



~510 m



443 m



324 m

*Bennu*

*Empire State Building*

*Eiffel Tower*

# How do we Navigate to Bennu?



Solar System  
Barycenter

$$\begin{bmatrix} \vec{x} \\ \vec{v} \end{bmatrix}_{SC,SSB}$$

$$\begin{bmatrix} \vec{x} \\ \vec{v} \end{bmatrix}_{E,SSB}$$

Earth

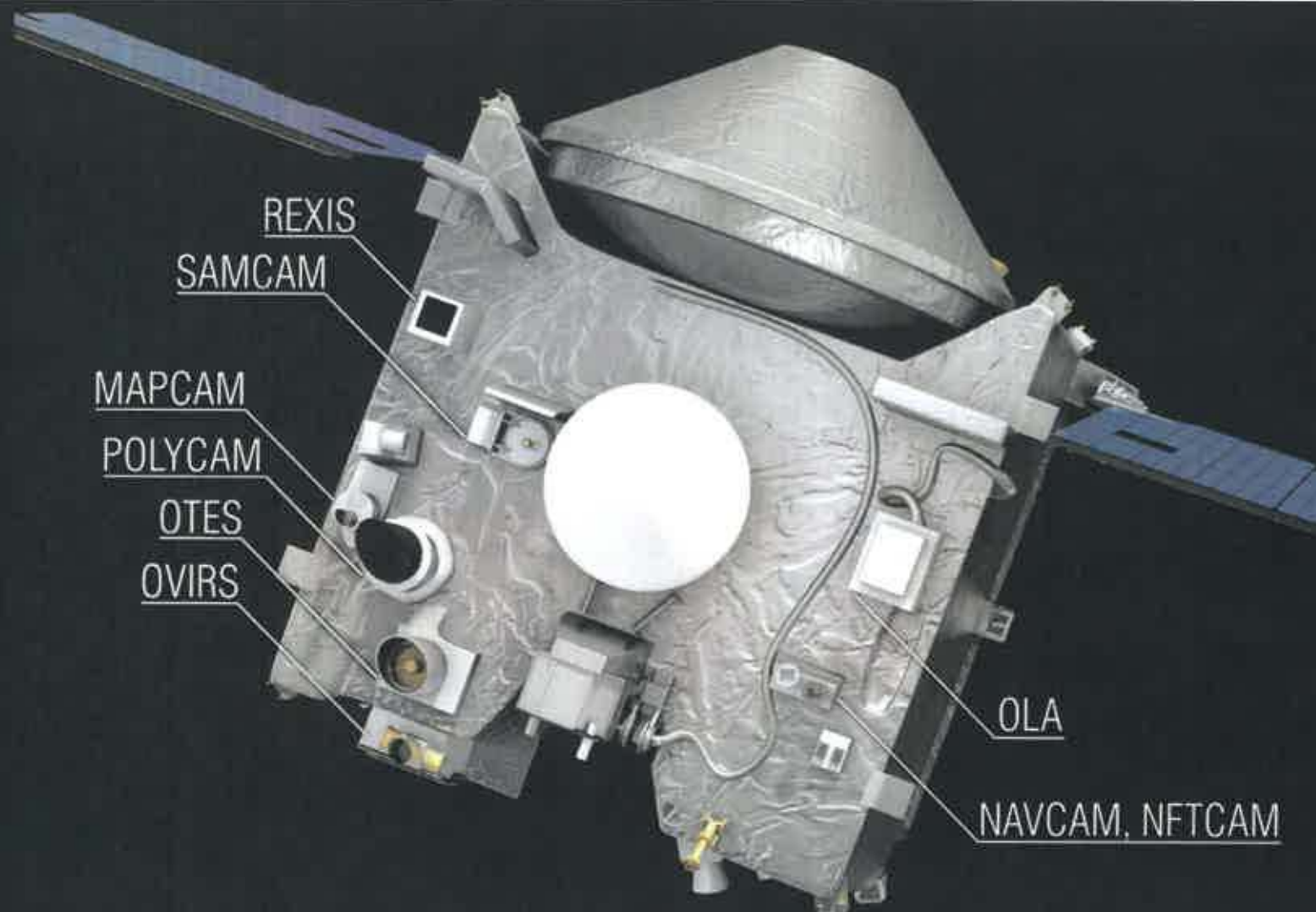
$$\begin{bmatrix} \vec{x} \\ \vec{v} \end{bmatrix}_{SC,E}$$

## Fundamental Navigation Data Products:

1. Range
2. Doppler
3. Delta-Differential One-way Range ( $\Delta$ DOR)
4. **Optical (Spacecraft-relative imaging)**

# Optical Navigation Techniques





REXIS

SAMCAM

MAPCAM

POLYCAM

OTES

OVIRS

OLA

NAVCAM, NFTCAM





# PROXIMITY OPERATIONS TO- DATE

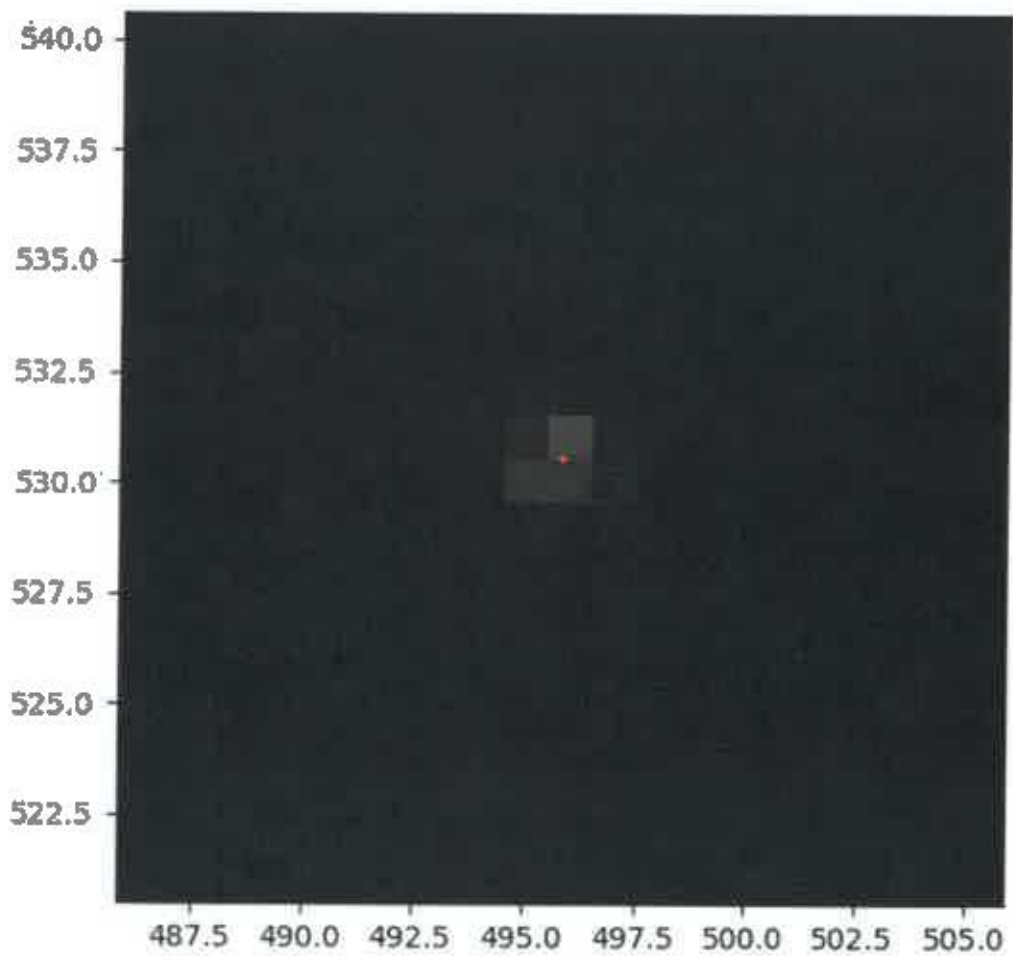


Bennu First Light (August 17<sup>th</sup>, 2018)

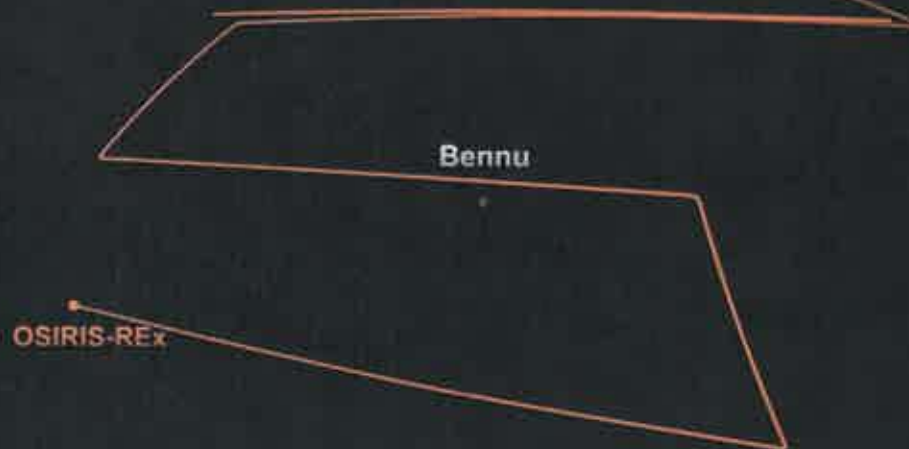
<https://www.asteroidmission.org/?latest-news=nasas-osiris-rex-begins-asteroid-operations-campaign>



PolyCam images during  
the Approach phase  
(Predicted shape model  
outline in red)



Orbit A Insertion  
2 x 1.5 km "Frozen" Terminator Orbit



**First application of a "frozen" orbit about a small body – set eccentricity to balance SRP perturbations and minimize changes in orbital elements**





# Record Setting Orbit



## CERTIFICATE

The smallest object to be orbited by a spacecraft is the asteroid 101955 Benu, which was confirmed to have a mass of 73.27 billion kg when the NASA spacecraft *OSIRIS-REx*, jointly operated by NASA, the University of Arizona and Lockheed Martin, entered its orbit on 31 Dec 2018.

OFFICIALLY AMAZING



## CERTIFICATE

The closest orbit of a planetary body was achieved by the NASA spacecraft *OSIRIS-REx*, jointly operated by NASA, the University of Arizona and Lockheed Martin, which moved into a 1.6 x 2.1 km orbit around the asteroid 101955 Benu on 31 Dec 2018.

OFFICIALLY AMAZING



## ProxOps View from Sun



## OREX Data

2019/01/06 20:56:00.0000 UTC

Distance to Benu	/	1.652 km
Distance to Earth (AU)	/	0.694
Distance to Sun (AU)	/	0.897
Speed wrt Benu (cm/s)	/	5.692
Speed wrt Earth	/	23.388 km/s
Speed wrt Sun	/	34.494 km/s
One Way Light Time	/	346.426 s
SPE Angle	/	75.122 deg
OREX Sun-North Latitude	/	-32.310 deg
OREX Sun-North Longitude	/	86.840 deg

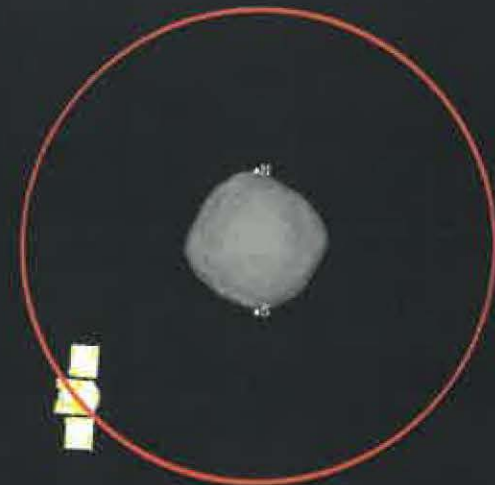
Record Setting Orbit

And again!

Latest Orbit Radius: ~900-m

### Orbit B View

2019/07/20 14:00:00.0000 UTC



### OREX Data

Distance to Bennu	,	0.936 km
Distance to Earth (AU)	,	1.290
Distance to Sun (AU)	,	1.343
Speed wrt Bennu (cm/s)	,	7.166
Speed wrt Earth	,	29.858 km/s
Speed wrt Sun	,	23.091 km/s
One Way Light Time	,	643.942 s
SPE Angle	,	45.341 deg
OREX Sun-North Latitude	,	-39.189 deg
OREX Sun-North Longitude	,	271.498 deg
Local Sun-North Solar Hour,		6.100


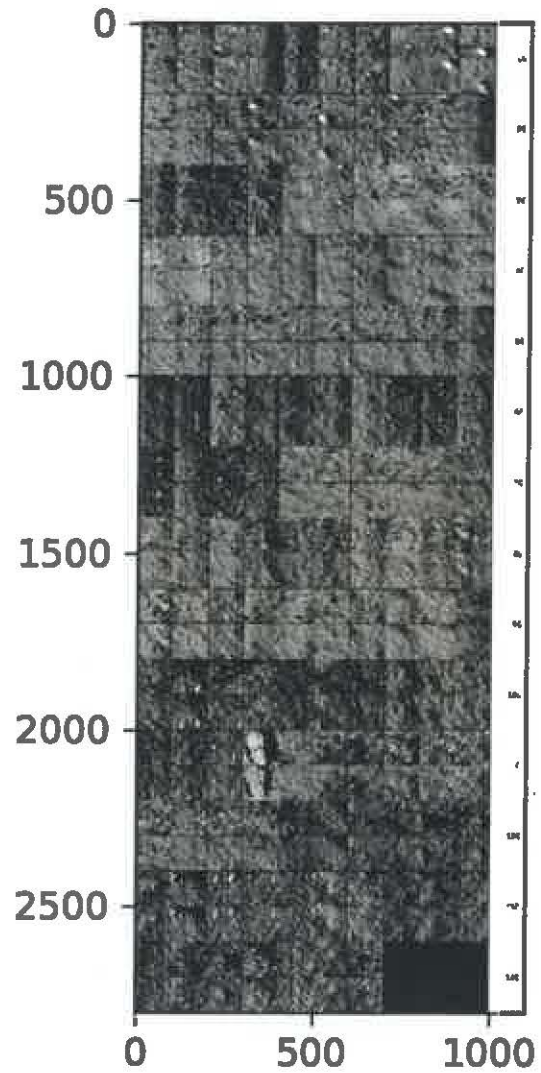
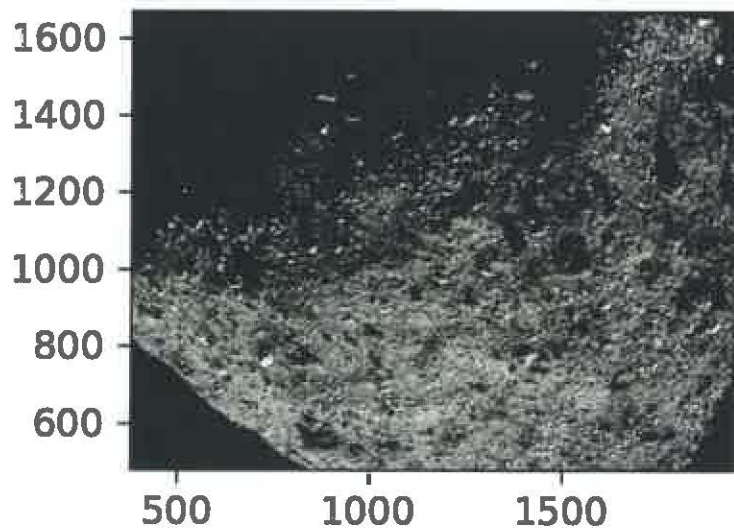
## Transition to Orbit B



NavCam OpNav  
images during the  
**Orbit B** phase

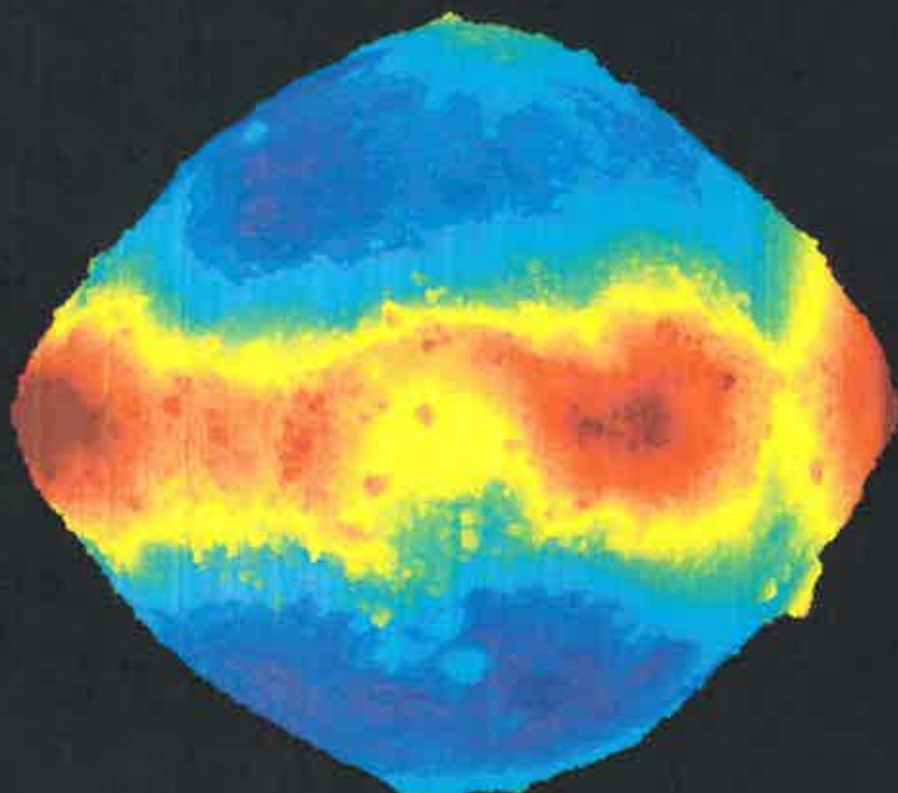
(images approx.  
every 2-hours,  
minus gaps for  
HGA passes)





Terrain-relative  
image processing  
via SPC in **Orbit B**





OSIRIS-REx Laser Altimeter (OLA) global mapping campaign in Orbit B

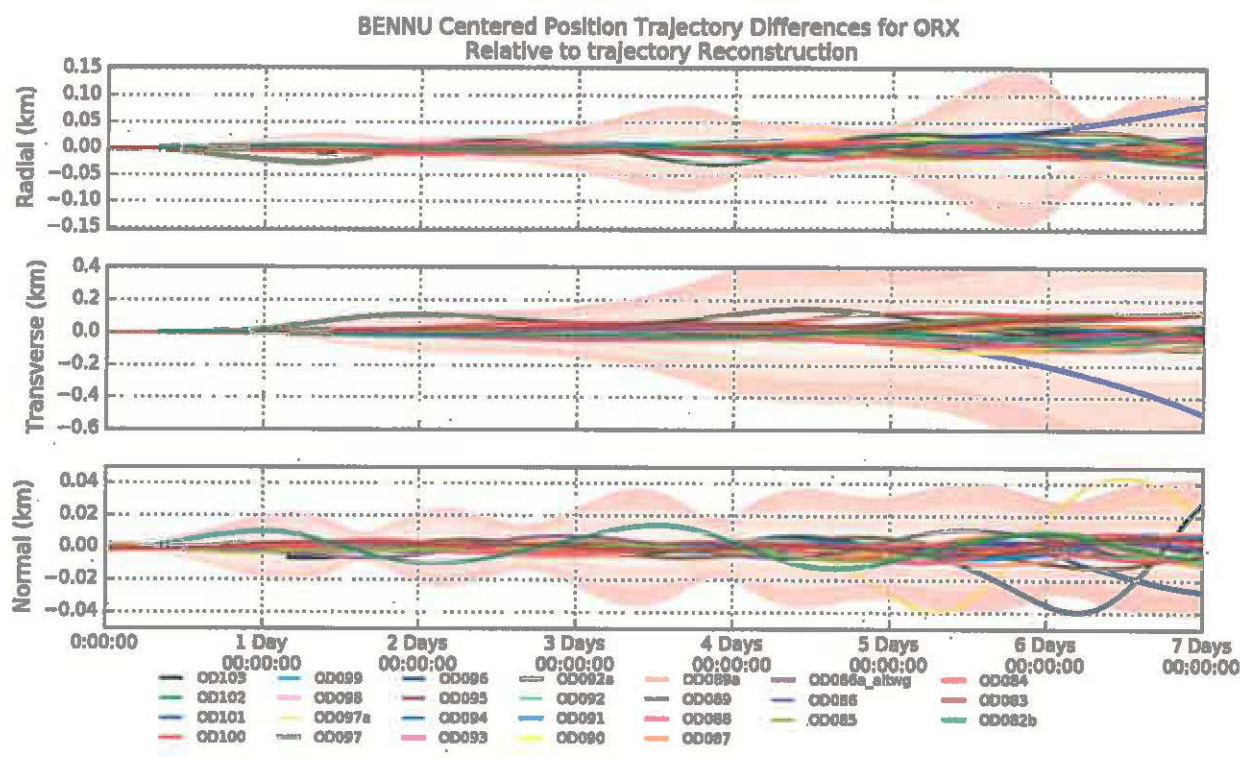
Starting to use high-resolution altimetry data to augment and verify navigation solutions



## Navigation Performance To-Date

- Achieving meter-level trajectory prediction accuracy in orbital phases over a few days
- Targeting for all survey and reconnaissance observations have been well within specifications
  - Successfully executed **64 prox ops maneuvers** to-date

### Orbit A Prediction Performance (Leonard, et. al. 2019)

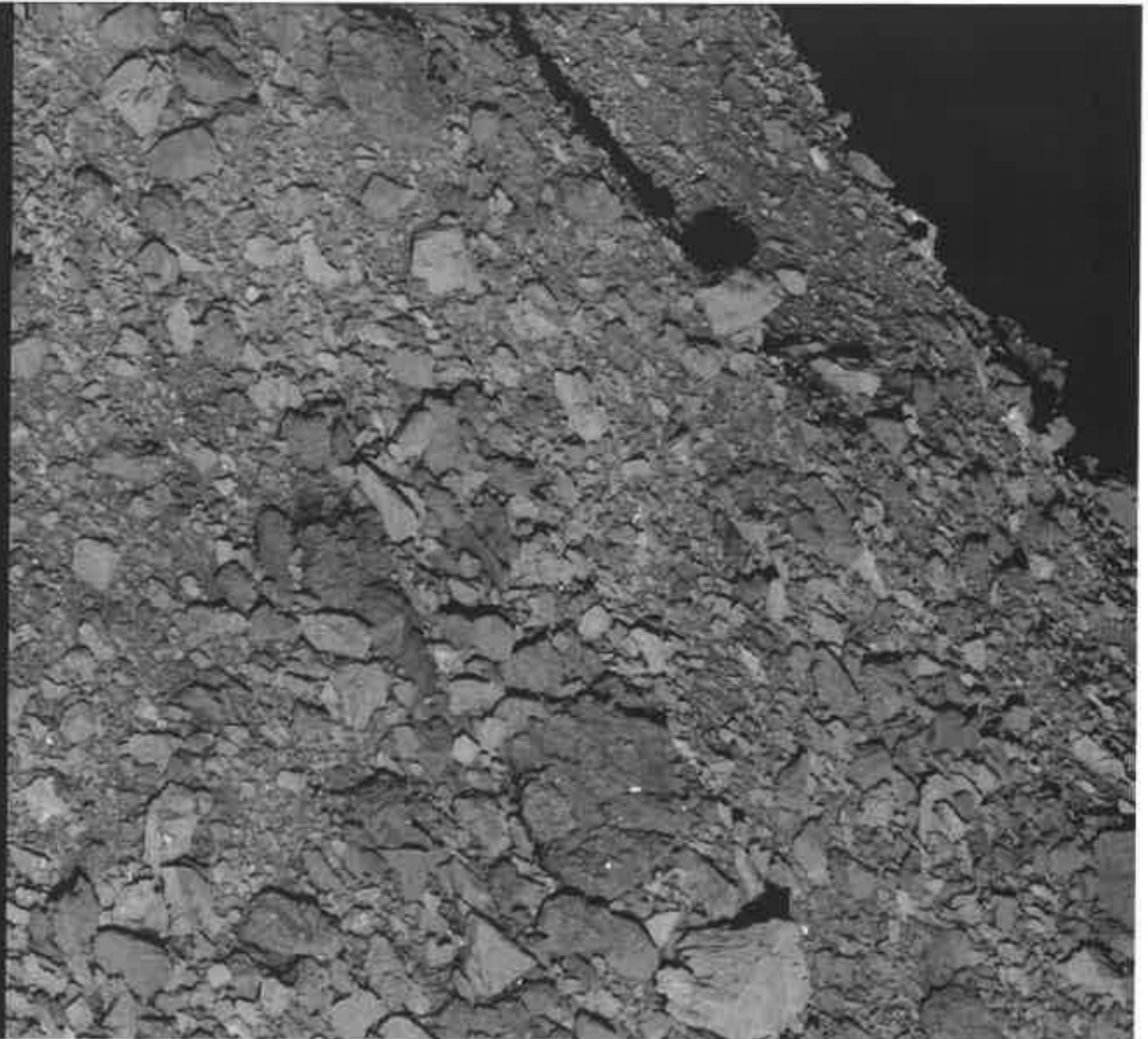




# **EARLY DISCOVERIES – IMPLICATIONS FOR NAVIGATION**

Bennu's surface is much more rugged than previously thought:

Driver for site selection and TAG navigation performance



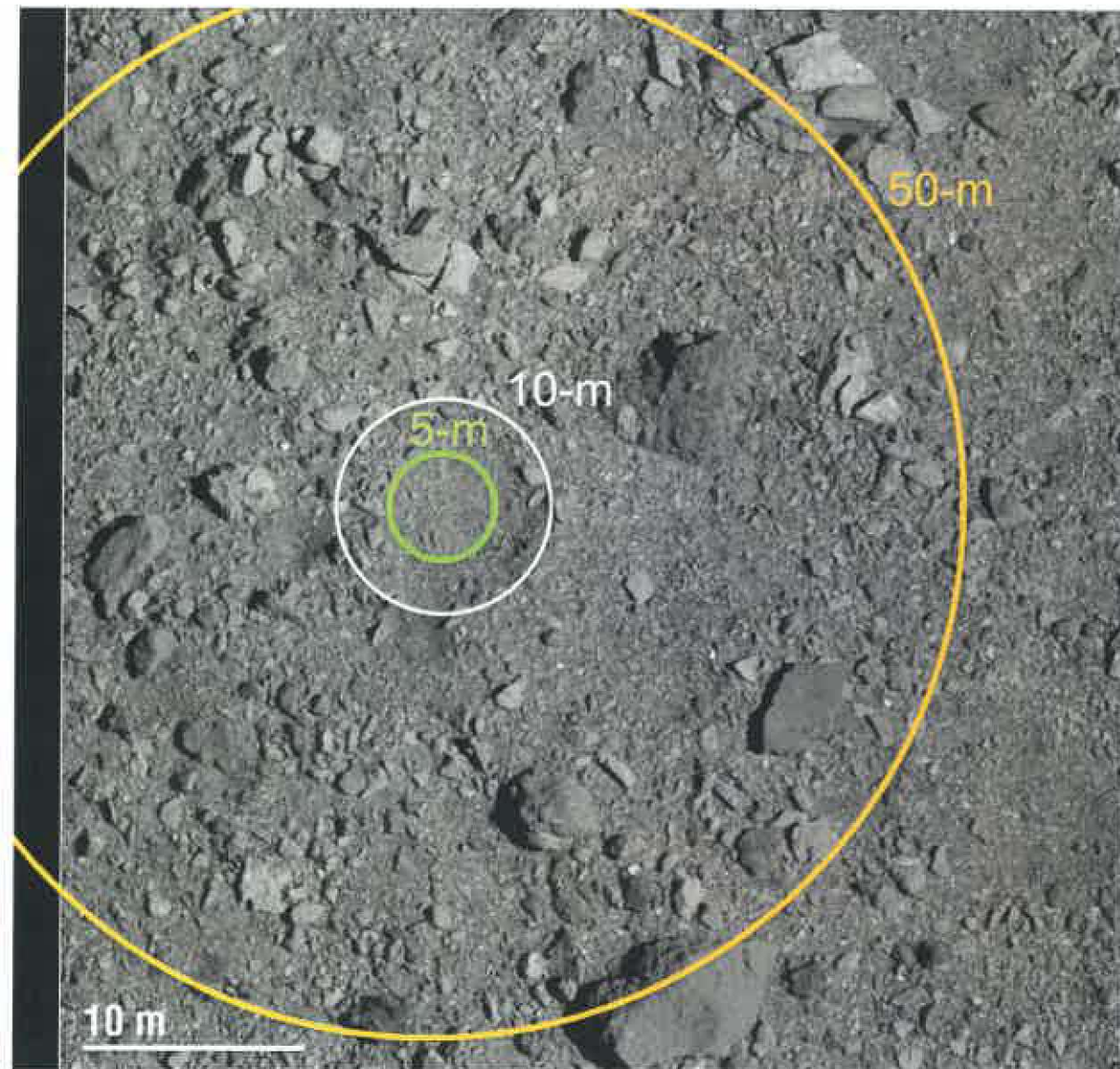




Original TAG Accuracy  
Requirement:  
50-m Diameter

*Bull's-Eye TAG:*

Onboard terrain-  
relative navigation  
and hazard avoidance



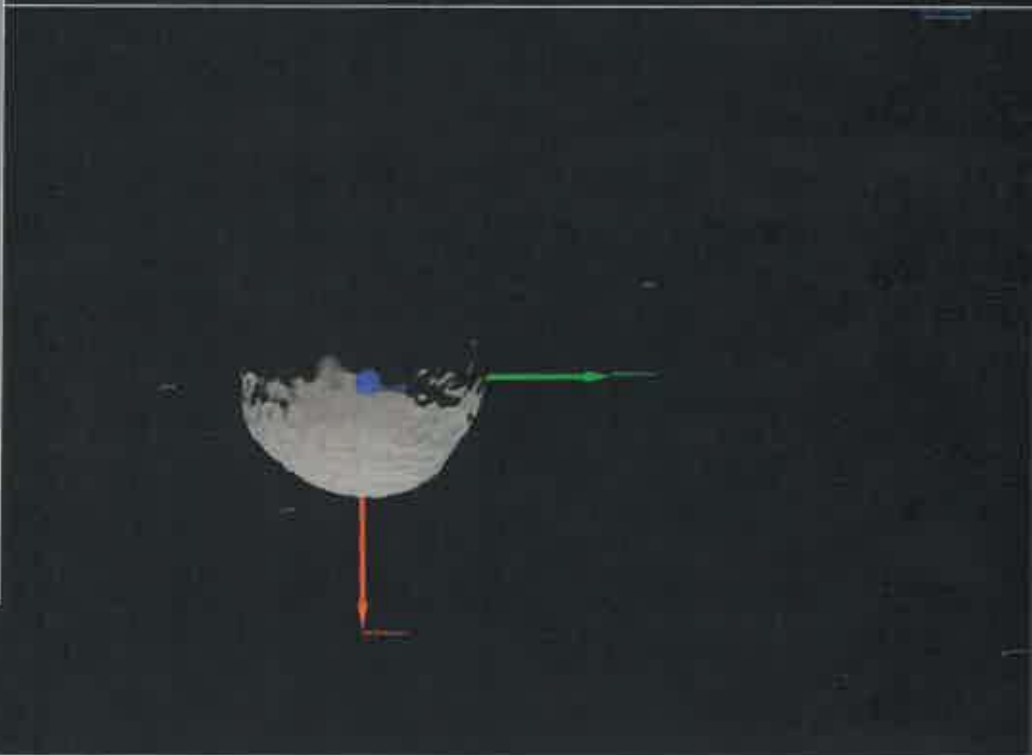
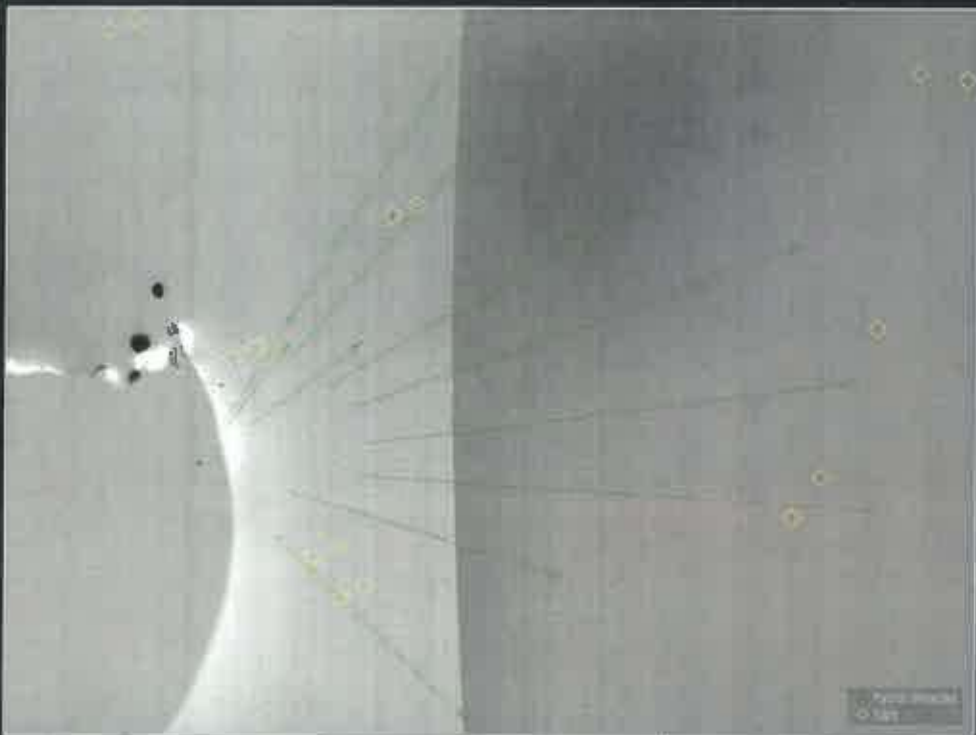
# Unexpected Discovery: Bennu is an Active Asteroid





# Optical Navigation Tools and Processes Utilized to Reconstruct Ejection Events

Visualization of Jan 19<sup>th</sup> Ejection Event



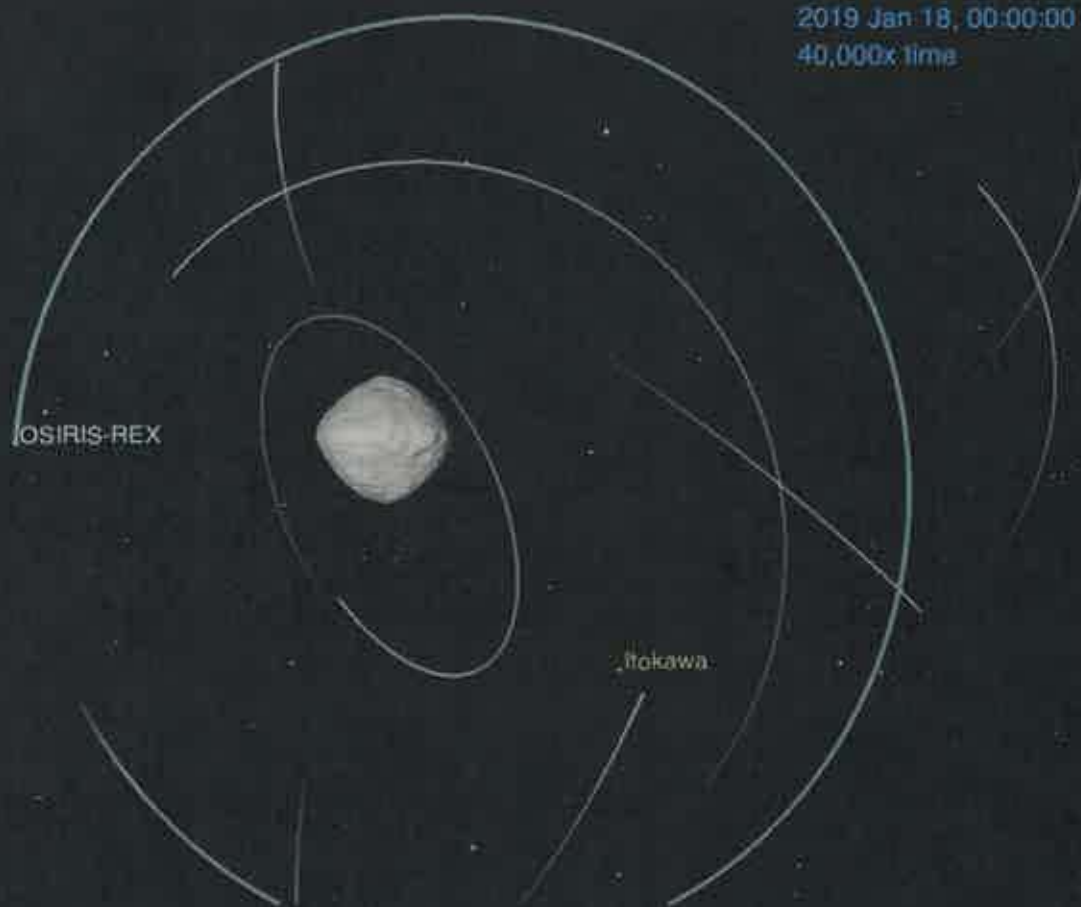
# Bennu

Distance: 3.86207 km

Bounding Radius: 287.3 m

2019 Jan 18, 00:00:00 UTC

40,000x time





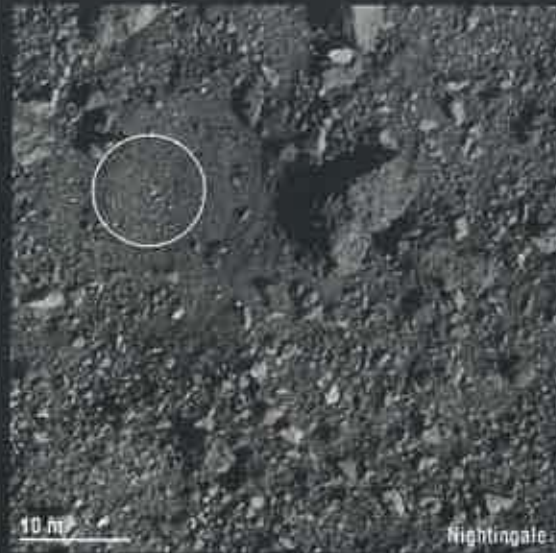


# CURRENT STATUS

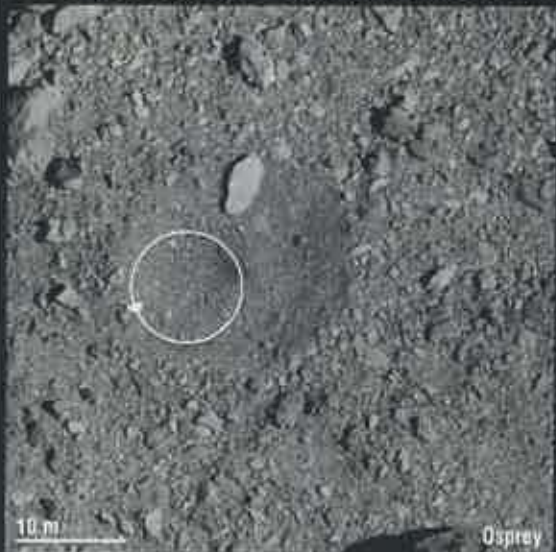
“Final Four”  
Candidate Sites  
selected in July,  
2019



Nightingale  
(DL15)



Osprey  
(DL06)



Kingfisher  
(CQ13)

Sandpiper  
(EX07)

OSIRIS-REX Recon View

2019/10/03 17:32:00.0000 UTC

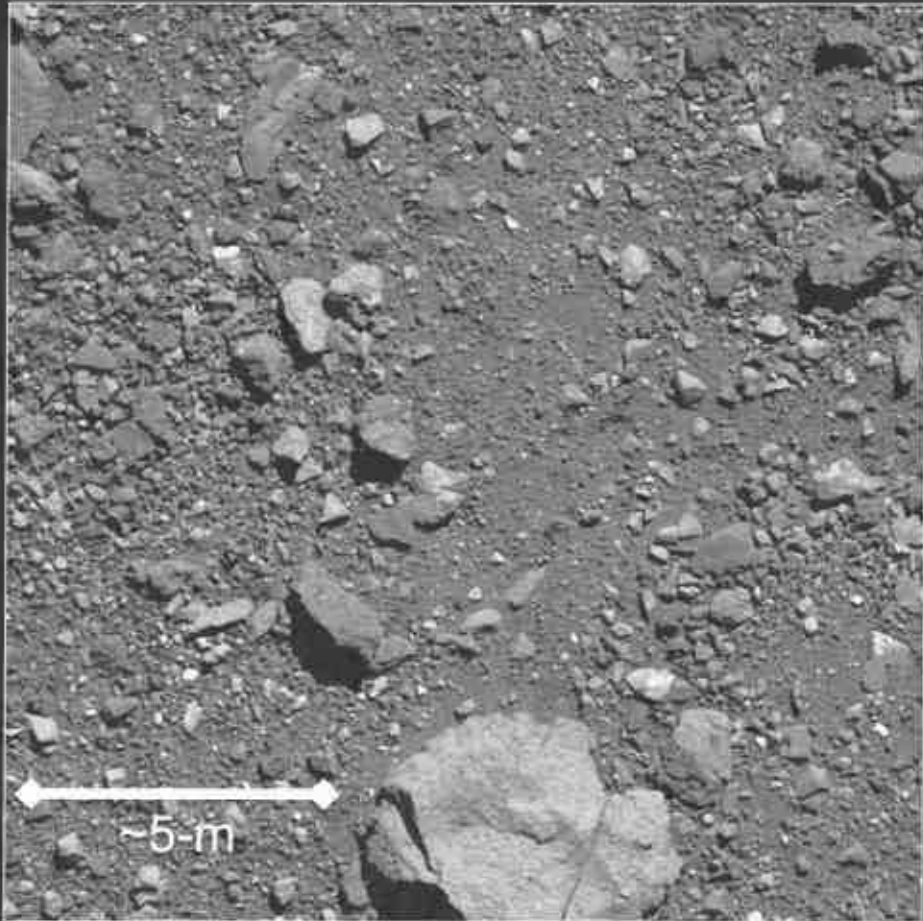
OSIRIS-REX



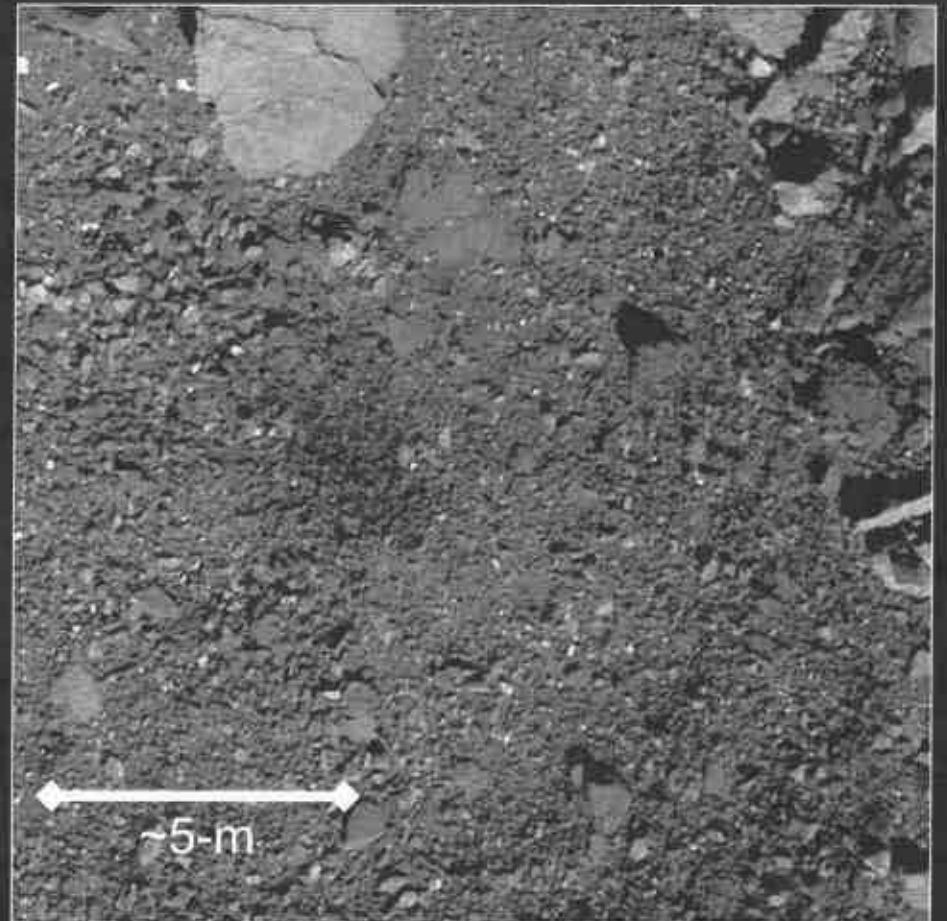
Recon A Phase:  
1-km Hyperbolic Flyby  
of Over Candidate Site  
October 3<sup>rd</sup> – 26<sup>th</sup>



Sandpiper (EX07): Recon A  
October 5<sup>th</sup>, 2019



Osprey (DL06): Recon A  
October 12<sup>th</sup>, 2019



Kingfisher (CQ13): Recon A  
October 19<sup>th</sup>, 2019



Replace with Kingfisher  
image, which should be  
available tomorrow

Nightingale (DL13): Recon A  
October 26<sup>th</sup>, 2019

**Final Recon A Flyby  
Executes Tomorrow:  
Nightingale (DL15)**

**Images will be available  
soon...**

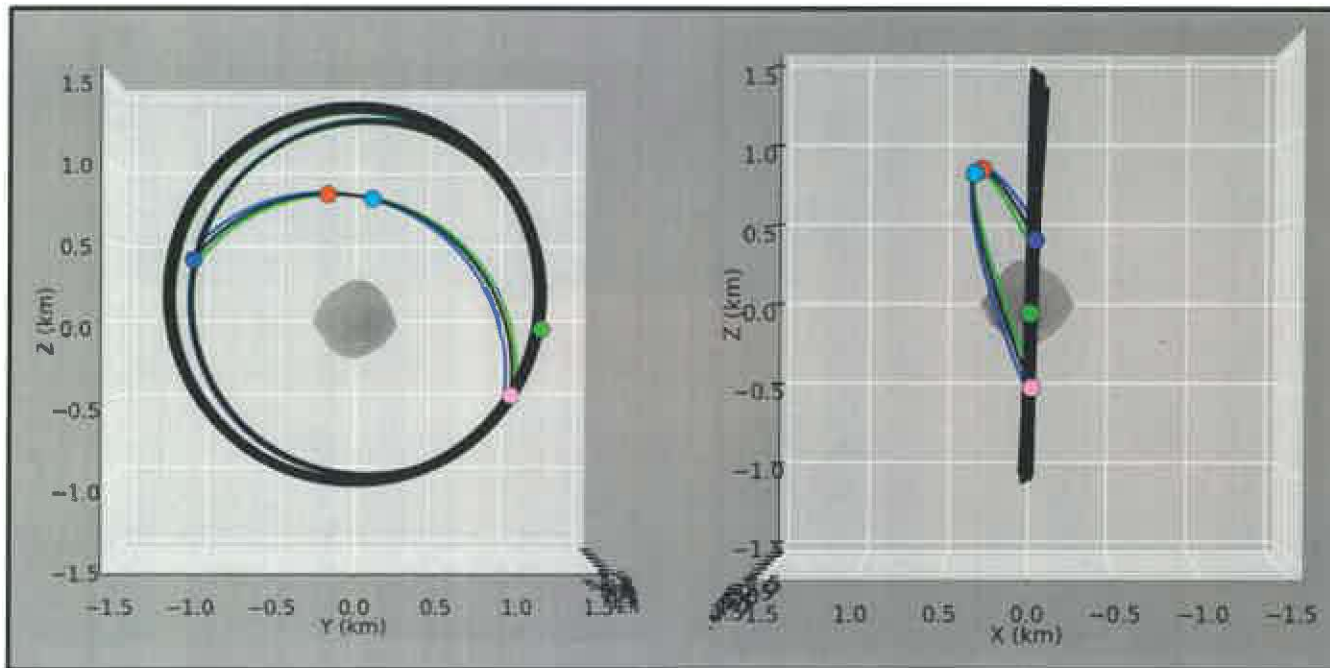


**NEXT STEPS**



## Medium & Low Reconnaissance

- Navigation & Science Planning Teams are currently designing Medium (~600-m) and Low (~225-m) altitude flybys of the Prime and Back-up sample sites
  - Scheduled for early-2020



Preliminary design of notional DL15 "Medium" (~600-m) flyby

Each flyby is ~12-hours from departure to recapture



Touch-and-Go (TAG):  
Collecting the Sample  
(mid-2020)





## Conclusions

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- The OSIRIS-REx mission has provided an up-close and breathtaking look at the near-asteroid 101955 Bennu
- Bennu's surface roughness has provided a challenge to site selection, leading to the baseline of "Bull's-eye TAG"
- Fortunately, navigation performance to-date has been exceptional
- High Reconnaissance Passes, which will be completed tomorrow, provide the necessary data to select a Prime and Back-up sample site
  - Medium and Low Reconnaissance passes early next year will provide additional data necessary to successfully perform TAG
- Rehearsals and TAG sample acquisition are scheduled for mid-2020



## JOIN THE MISSION ON THE WEB!

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AsteroidMission.org



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# OSIRIS-REx

asteroid sample-return mission