



Navigating an Asteroid

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March 20, 2021

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NASA'S GODDARD SPACE FLIGHT CENTER

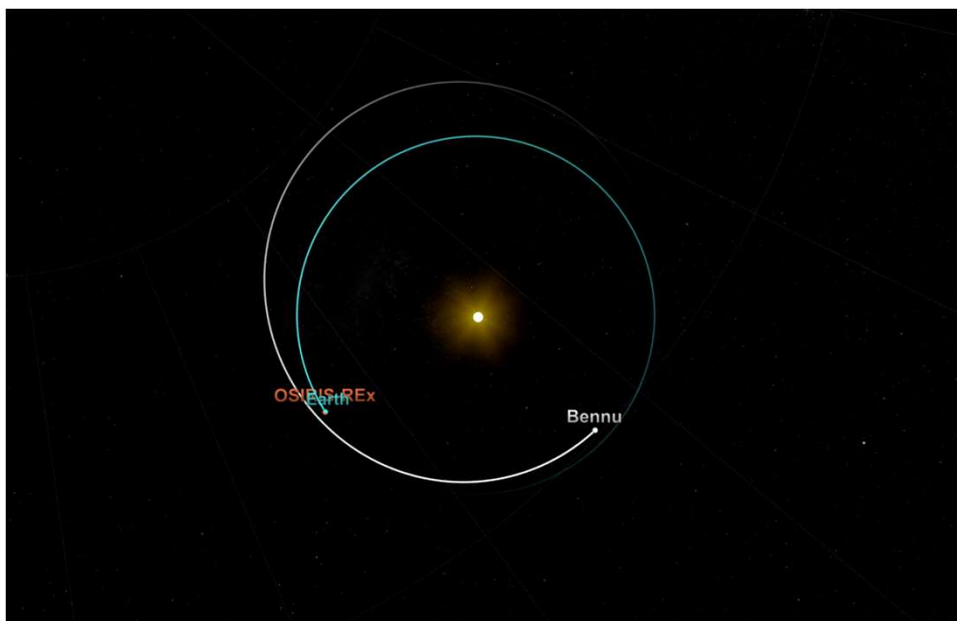
LOCKHEED MARTIN



About OSIRIS-REx and Bennu

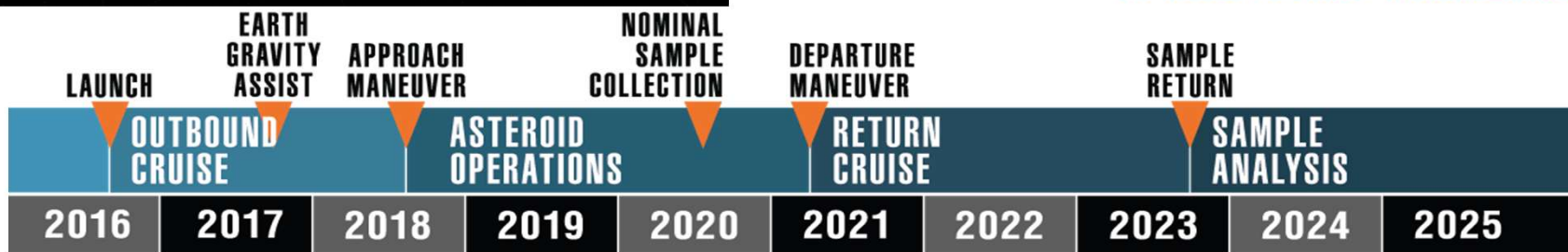


OSIRIS-REx Overview



- **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





How Tall is Asteroid Bennu?



~510 m



443 m



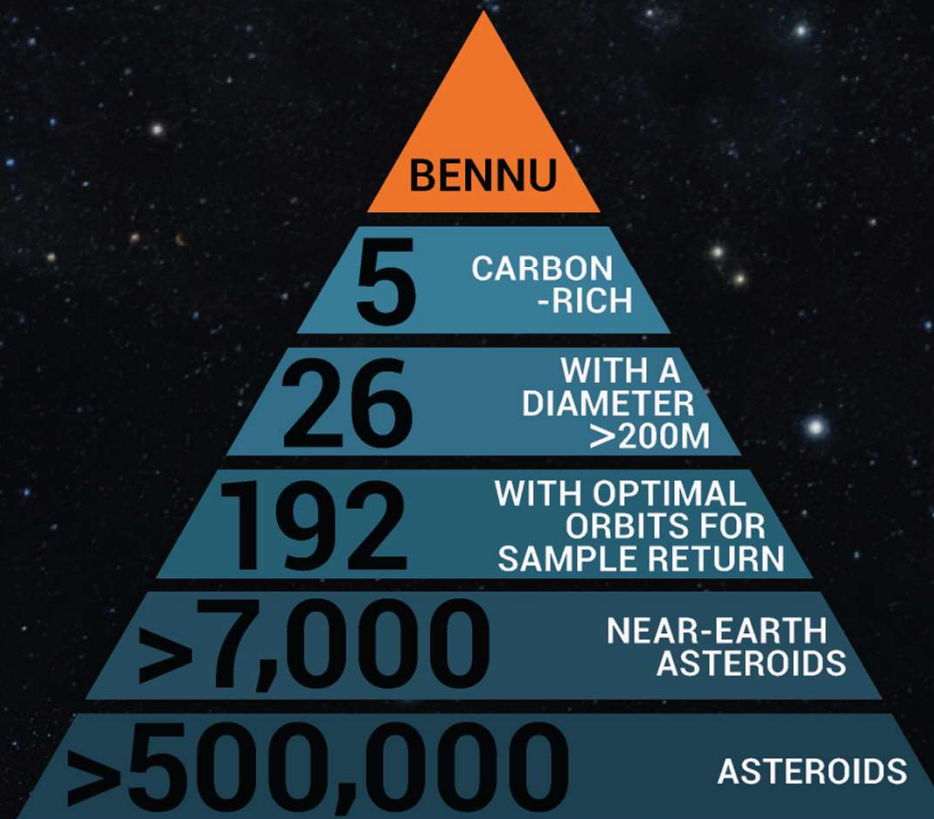
324 m

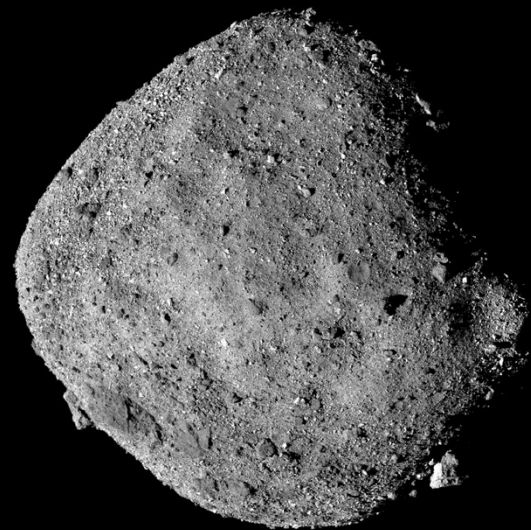
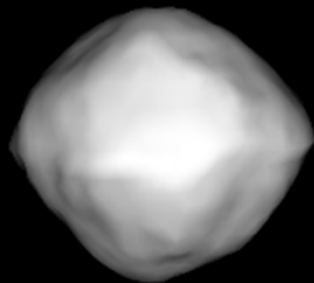
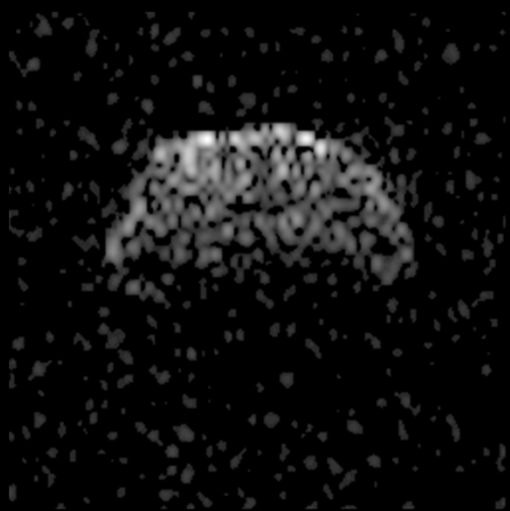
Bennu

*Empire State
Building*

Eiffel Tower

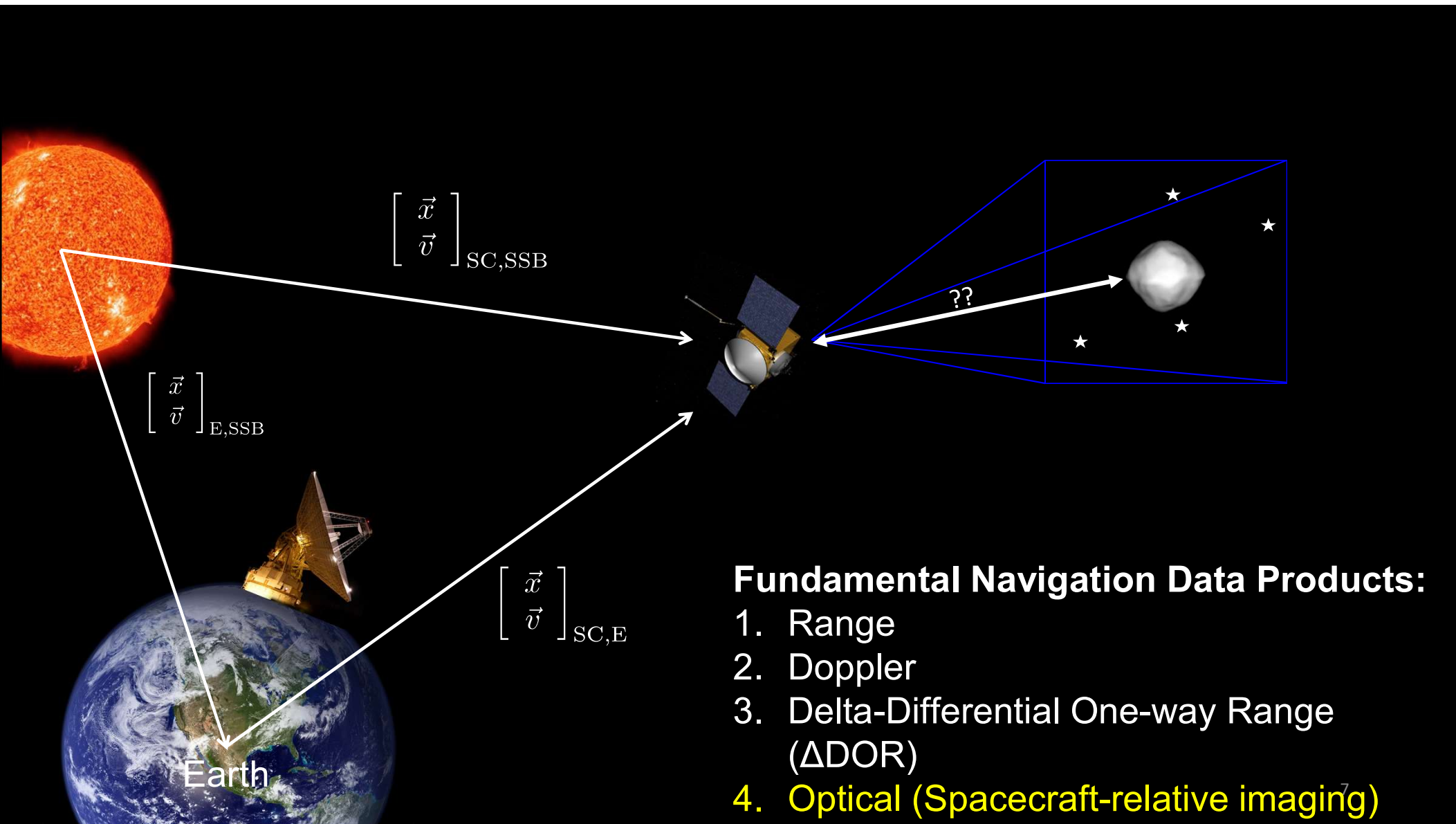
How Was Asteroid Bennu Chosen?



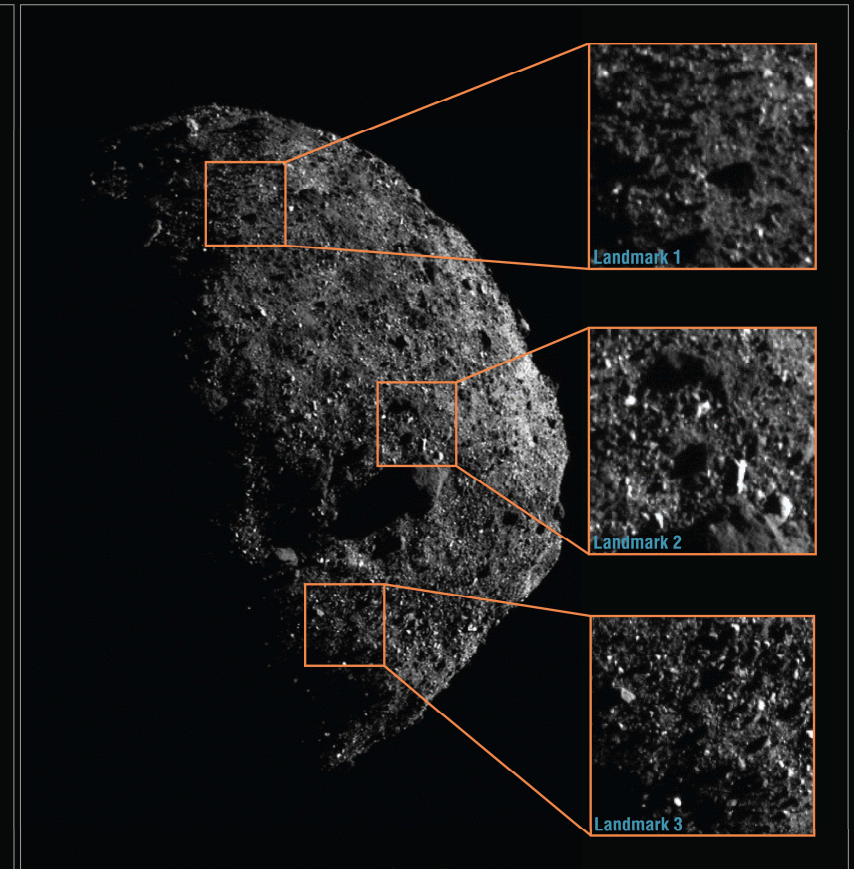
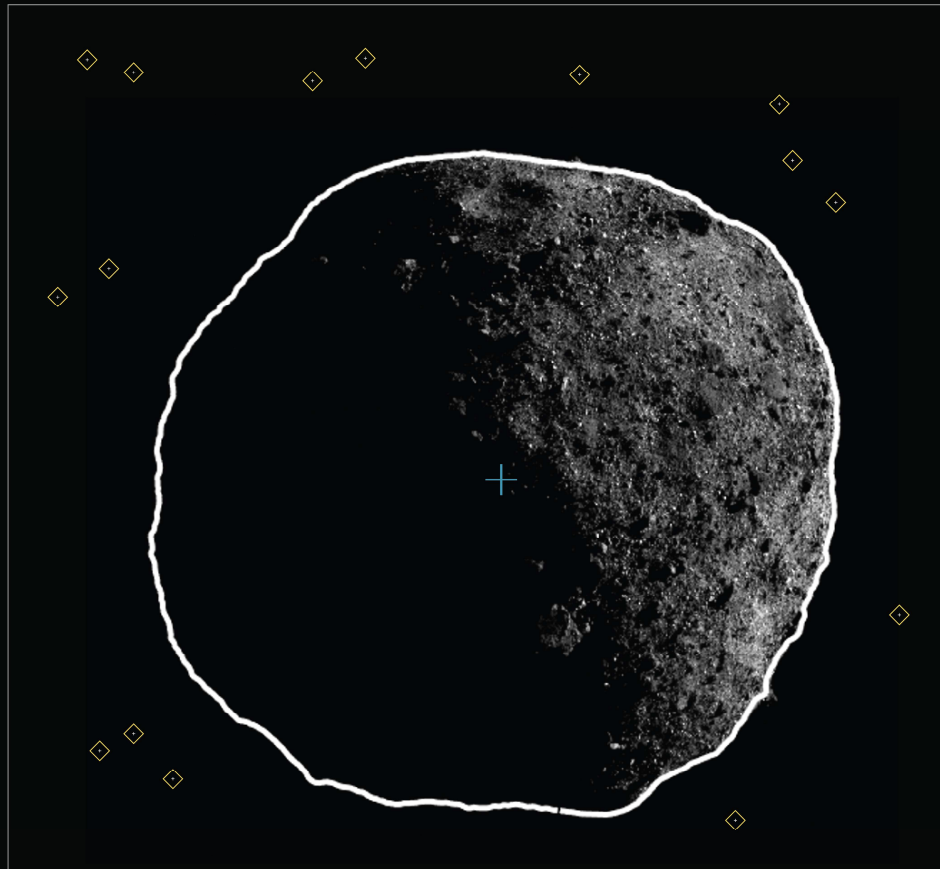




Operating at Bennu



Optical Navigation Techniques





OSIRIS-REx | ASTEROID OPERATIONS TIMELINE



OSIRIS-REx: LOWEST ALTITUDES

1500 1250
<BBD
3060 m
ORBITAL A
1350 m

PHASE START
ORBITAL A
JAN
2019
DETAILED SURVEY: BASEBALL DIAMOND (BBD)
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
2019



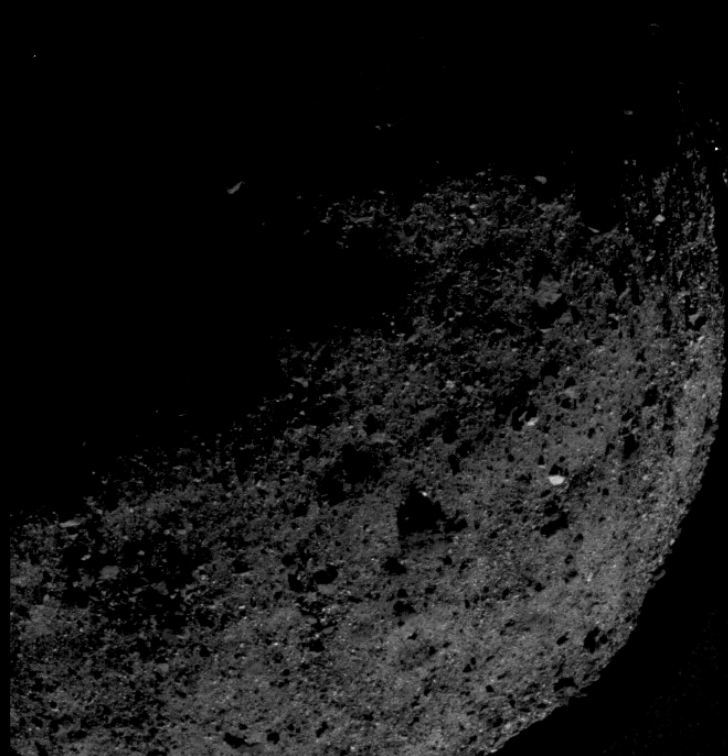
250
RECON C
250 m
CP
50 m
MP
40 m
TAG

CHECKPOINT (CP) REHEARSAL
MAY
JUN
JUL
AUG
SEP
OCT
2020
MATCHPOINT (MP) REHEARSAL
SAMPLE COLLECTION (TAG)

SPACECRAFT NOT TO SCALE



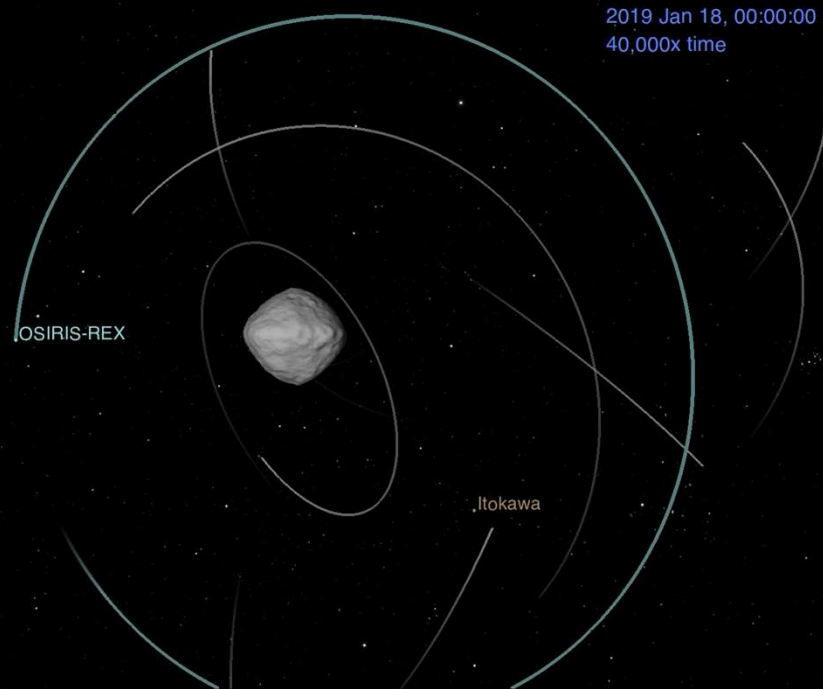
Challenges and Surprises from Bennu



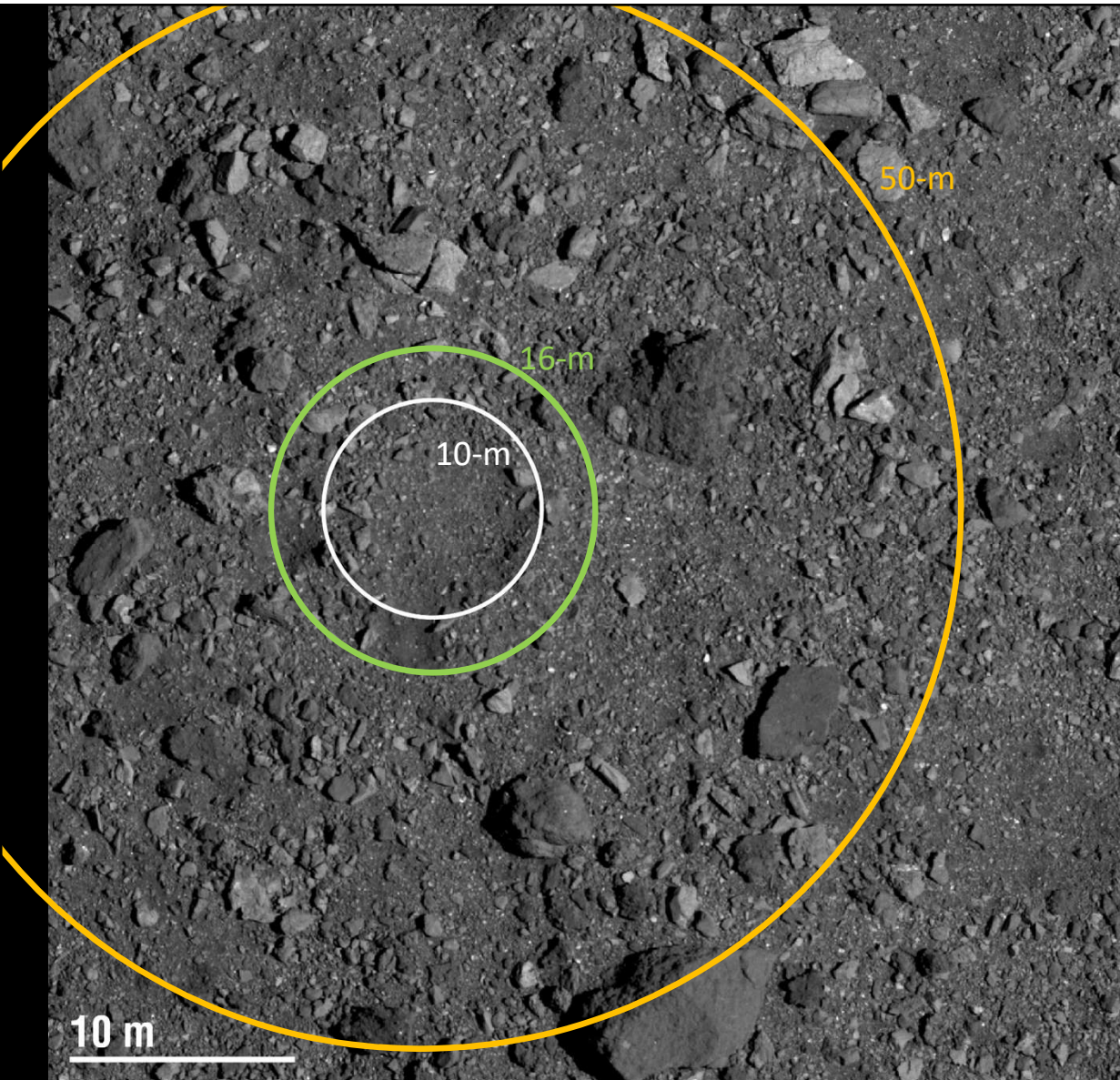
Bennu

Distance: 3.86207 km

Bounding Radius: 287.3 m



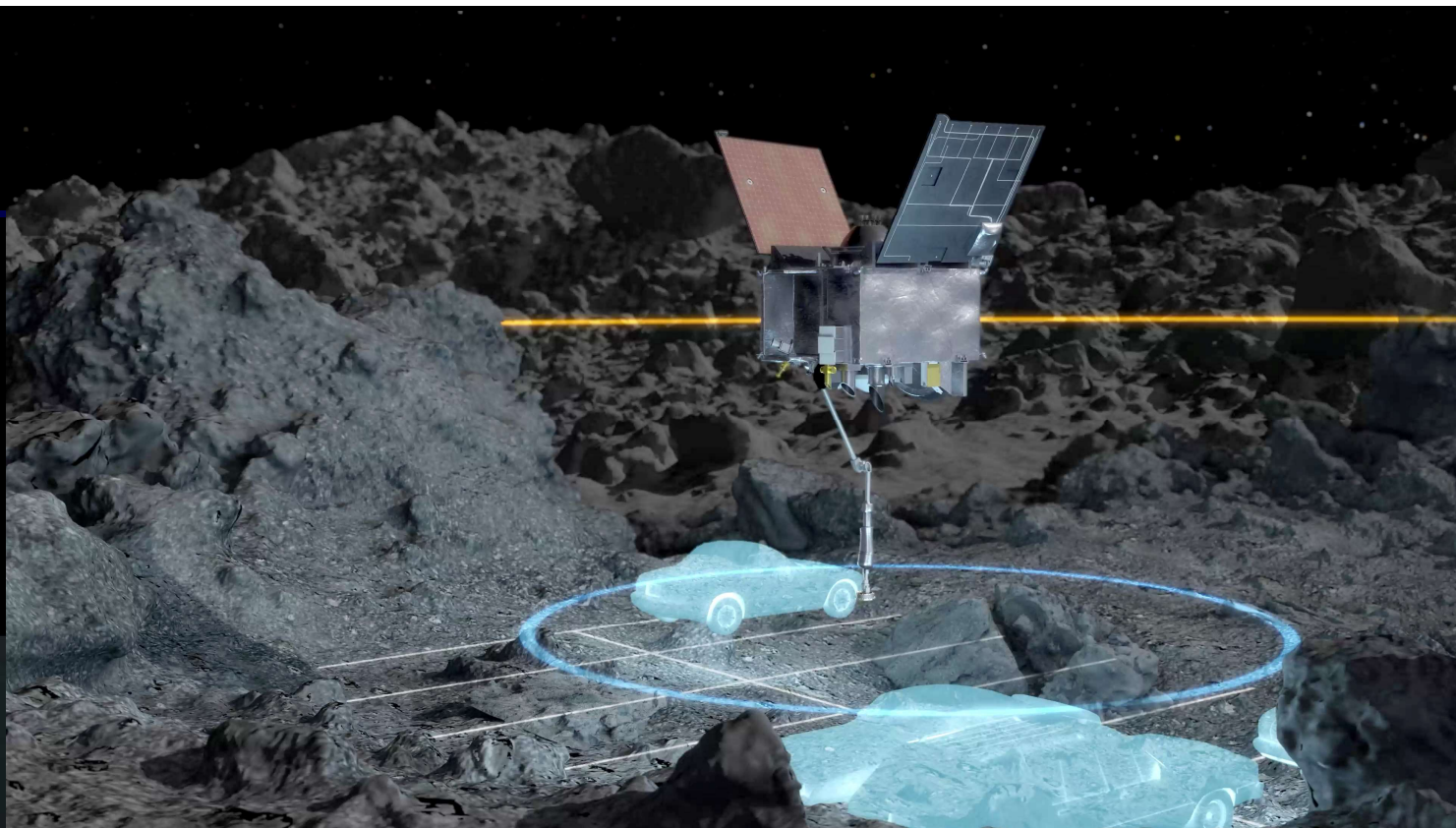
2019 Jan 18, 00:00:00 UTC
40,000x time



Original TAG Accuracy
Requirement:
50-m Diameter

Bull's-Eye TAG:

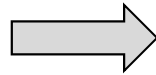
Onboard terrain-
relative navigation and
hazard avoidance





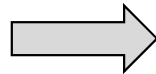
How we solved the problems of Bennu

TAG sites much smaller than expected



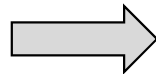
Switch from lidar to image based onboard navigation
Improve navigation performance!

Boulders and rock hazards everywhere



Add hazard map abort capability

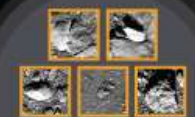
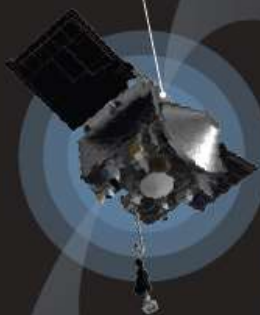
Not enough fine-grained, sampleable material



Pick the least-bad site.
Improve navigation performance.
Cross our fingers!



ONBOARD
IMAGE
CATALOG



FEATURES IDENTIFIED
...
MATCHING
COMPLETED

KNOWN BENNU FEATURES

SPACECRAFT'S
POSITION &
CONTACT POINT
UPDATED

SPACECRAFT LIVE VIEW



AUTONOMOUS
OPTICAL NAVIGATION

NATURAL FEATURE TRACKING

NAVIGATION DURING SAMPLE COLLECTION

HAZARD MAP

TARGET AREA SAFE:



TAG SURFACE



TARGET AREA UNSAFE:



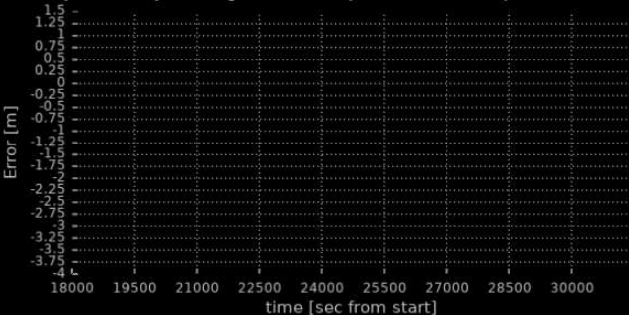
WAVE-OFF



GSFC/Freespace Visualization for OSIRIS-REx TAG Event

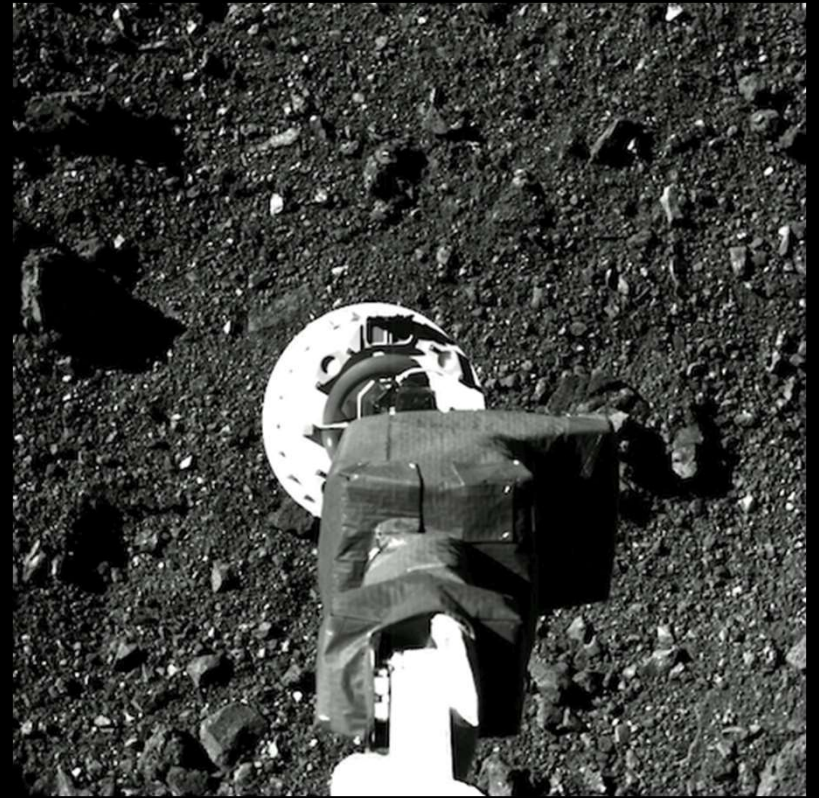
NFT NavCam

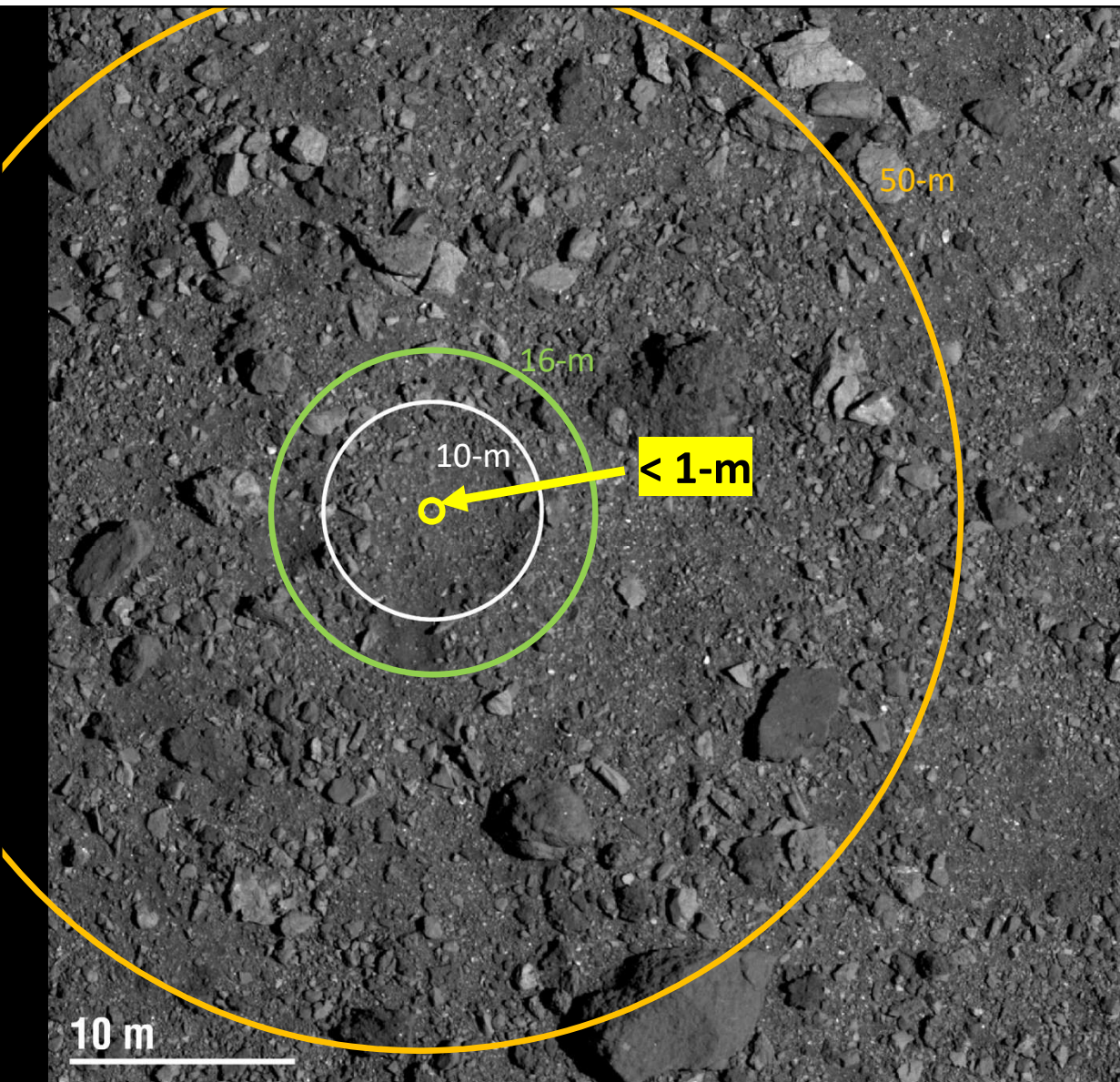
(NFT-Pred) Errors [Blue=Radial, Green=In-Track, Red=X-Track]



[orange]: Reconstructed Trajectory
[green]: Late Update Trajectory
NFT NavCam GSD [cm/px]: 23.865.
Range to Surface [m]: 828.902
Range to TAG [m]: 1222.722
20-Oct-2020 13:30:02 SCET UTC





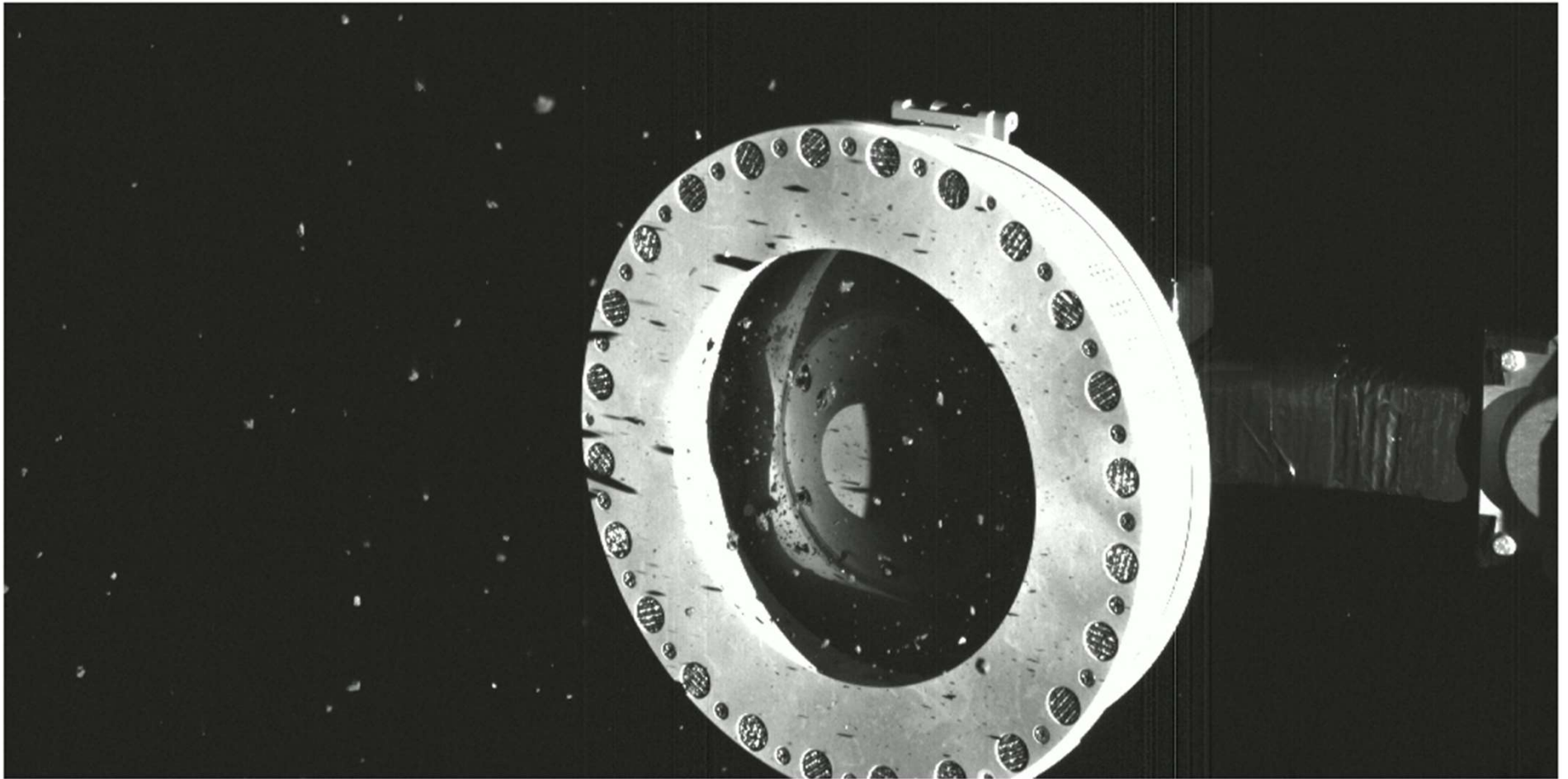


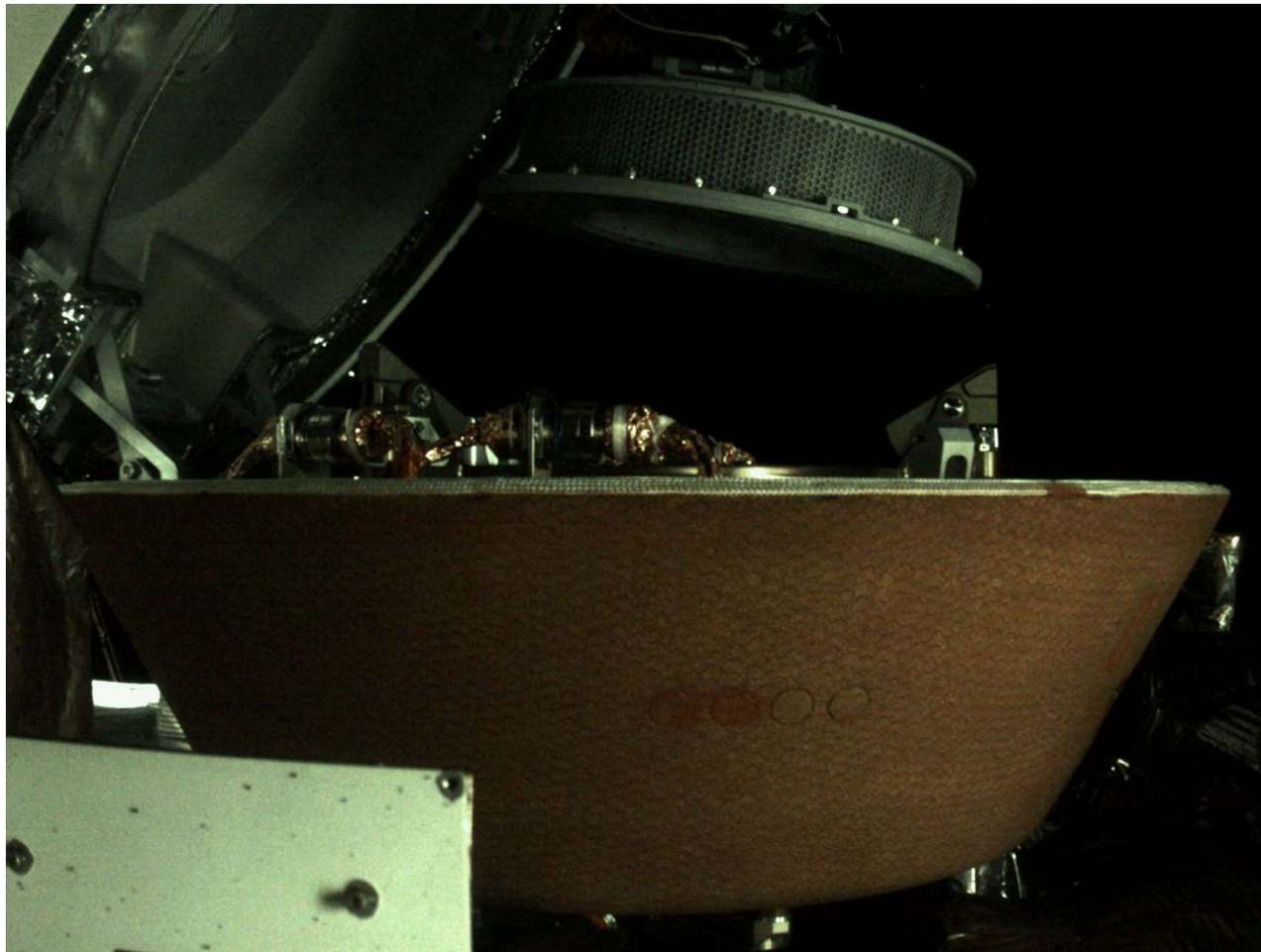
Original TAG Accuracy
Requirement:
50-m Diameter

Tag Performance:
< 1 meter



Contingency identified – mass loss during TAGSAM imaging





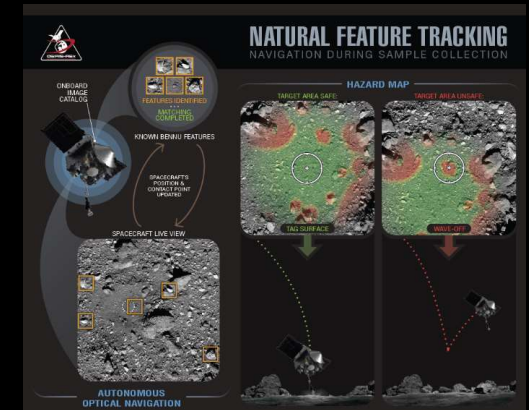
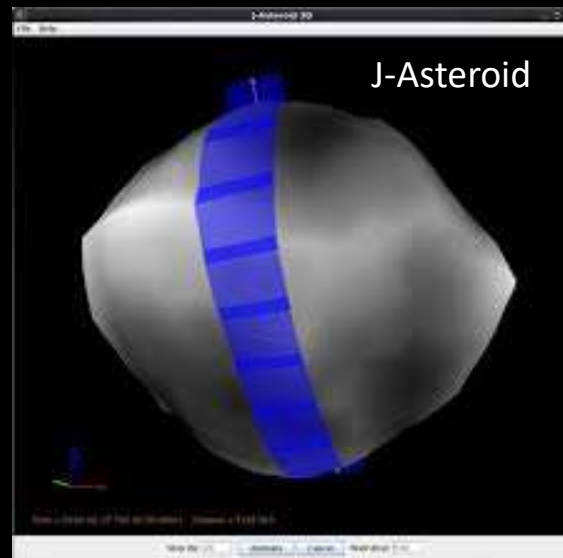
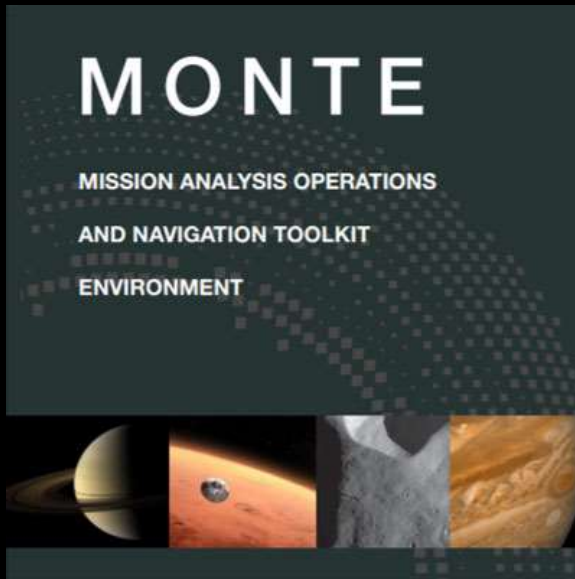




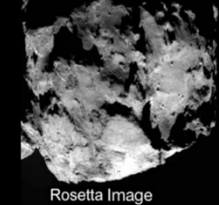
How does programming play into
all of this?



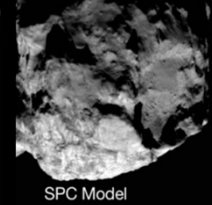
Everywhere



Stereophotoclinometry



Rosetta Image

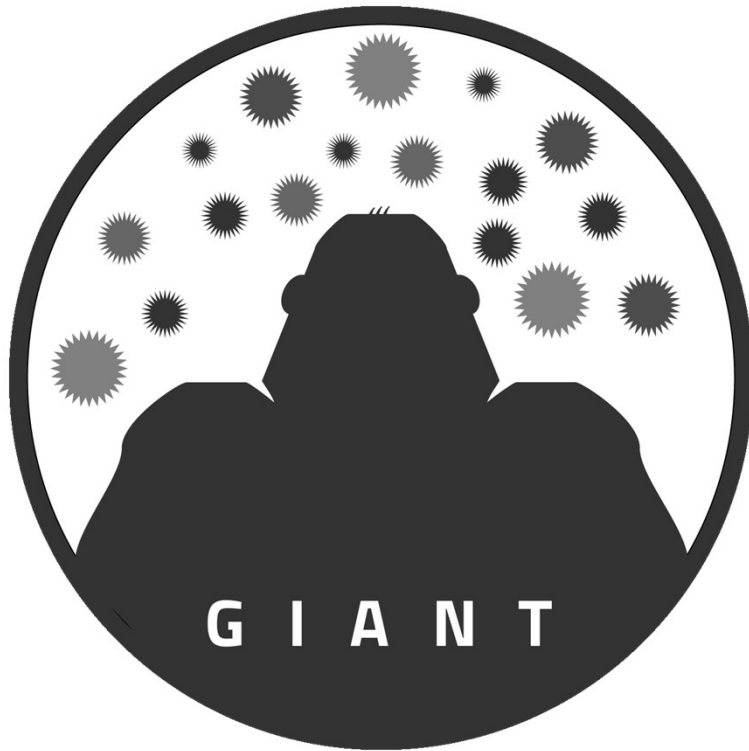


SPC Model



Everywhere

- Fortran
- Python
- Bash
- CSH
- Java
- HTML
- C
- C++
- JavaScript
- SQL
- MATLAB
- Assembly
- CSS
- XML
- OpenGL Shading Language
- VHDL/Verilog
- ReST
- LaTeX



- Designed/wrote/maintain our ground-based optical navigation library in Python/Cython
 - 13149 lines of python code + 12314 lines of comments/documentation + 9787 lines of python code for unit testing
 - 2071 lines of cython code + 1398 lines of comments/documentation
- Designed/wrote/maintain our mysql database and interface for spacecraft data
 - 6954 lines of python (sqlalchemy) + 1906 lines of comments
- Maintain a library of 20-30 bash scripts for data manipulation/automation/etc.
- + Other miscellaneous tools



How did I end up here?



Undergraduate and Masters in Aerospace Engineering.



Graduate research in the (defunct) Applied Space Exploration Lab on optical navigation for NASA's Orion EM-1 mission (un-manned mission around the moon)



2 Summer internships at GSFC (starting in my first year of Masters work)



Pathways internship at Goddard (co-op) my last year of Masters work -> conversion to full time civil servant.



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