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Contact with Bennu! Flight Performance Versus Prediction of OSIRIS-REx TAG Sample Collection

Kevin E. Berry[1], Kenneth M. Getzandanner[2], Michael C. Moreau[3], and Samantha M. Rieger[4]
NASA Goddard Space Flight Center Code 595, Greenbelt, MD, USA

Peter G. Antreasian[5], Coralie D. Adam[6], Daniel R. Wibben[7], Jason M. Leonard[8], Andrew H. Levine[4], Jeroen L. Geeraert[9], John Y Pelgrift[9], Leilah K McCarthy[10], and Eric M Sahr[10]
KinetX, Inc., Simi Valley, CA, USA

David A. Lorenz[11]
KBR Inc., Greenbelt, MD, USA

Dante S. Lauretta[12]
University of Arizona, Tucson, AZ, USA

The Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) mission collected a sample from the surface of the near-Earth asteroid (101955) Bennu in late 2020. Bennu challenged the team with a surface that was much rockier than expected, resulting in modifications to the prelaunch design of the Touch And Go (TAG) sequence. Following enhancements in onboard trajectory correction, ground-based navigation, and maneuver execution error modeling, the spacecraft was delivered to the chosen TAG site within 1 m of the target, and a sample was successfully collected on the first attempt. This paper provides a comprehensive description of all flight dynamics aspects of TAG trajectory planning and execution. It also describes hazard map generation and how that combined with error analysis results to predict the probability of safe contact before TAG and the onboard wave-off determination during TAG.

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[1] OSIRIS-REx Flight Dynamics TAG Analysis Lead
[2] OSIRIS-REx Flight Dynamics System Manager
[3] OSIRIS-REx Deputy Project Manager
[4] OSIRIS-REx Trajectory and Maneuver Analyst
[5] OSIRIS-REx Navigation Team Chief
[6] OSIRIS-REx TAG Navigation Manager
[7] OSIRIS-REx Trajectory and Maneuver Design Lead
[8] OSIRIS-REx Orbit Determination Lead
[9] OSIRIS-REx Orbit Determination Analyst
[10] OSIRIS-REx Optical Navigation Analyst
[11] OSIRIS-REx TAG Campaign Lead
[12] OSIRIS-REx Principal Investigator

I. Introduction

The Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx) mission is a NASA New Frontiers mission that launched in 2016 to rendezvous with the near-Earth asteroid (101955) Bennu in late 2018. The plan was to spend 4 months in various orbits collecting surface data for sample site selection, followed by 4 months of low altitude reconnaissance flybys and sample collection rehearsals, culminating with the TAG (Touch And Go) sample collection in August of 2019. Prior to launch, the TAG accuracy requirement was to deliver the spacecraft within 25 m of a selected sample site. This requirement could not be met without onboard autonomy, which led to the addition of a simple LIDAR (Light Detection and Ranging) based closed-loop control algorithm that corrected for in-track and radial dispersions. [1] Detailed Monte Carlo analysis with conservative error estimates had shown TAG position errors in the range of 15–22 m for sites distributed across the surface, which met the 25 m requirement with a healthy margin. [2] The project also developed a backup closed-loop control algorithm that used NFT (Natural Feature Tracking), which provided higher accuracy at a higher risk due to the increased complexity. [3]

Upon arrival at Bennu, the surface was found to be much rockier than expected. [4] The original 25 m TAG requirement was found to be insufficient, since the largest hazard-free sites were no larger than 8 meters in radius. To solve this new problem, the project re-evaluated all aspects of flight system performance to account for the demonstrated performance of the spacecraft and navigation prediction accuracies. Also, the project baselined NFT instead of LIDAR to provide the onboard navigation state update during the TAG sequence and made improvements to the NFT system to improve accuracy and perform a hazard avoidance assessment. [5] After a redesigned proximity operations campaign, the spacecraft successfully made contact with the surface of Bennu and collected a sample on October 20 of 2020 on our first attempt. [6]

II. Trajectory Design

Prior to TAG, the spacecraft was orbiting Bennu in a “frozen orbit” that was slightly offset from the Bennu solar terminator plane. This orbit was designed to balance the perturbations from solar radiation pressure with the low gravity of the asteroid, providing orbit stability over a period of several months. [7] The frozen orbit parameters were calculated by finding an equilibrium solution to the Lagrange planetary equations such that none of the Keplerian orbit parameters evolve over time in the Bennu-Sun rotating frame, with a result that had an eccentricity of roughly 0.16 as is shown in Fig. 1.

The TAG trajectory was designed to fly across the illuminated side of Bennu, departing from the frozen orbit at a latitude that is opposite that of the TAG site. To arrive at the surface with the optimal lighting conditions, orbit departure must occur at a specific local solar time. These constraints on orbit departure latitude and time required a pair of small phasing burns placed at 7 days and 3 days prior to orbit departure. [8]

The TAG sequence consisted of a burn to depart orbit at roughly 1 km from Bennu’s center, two burns to target the TAG site position and TAG velocity, the touchdown of the sample acquisition mechanism on the surface of Bennu, as triggered by a sensor confirming contact and thereby causing the firing of a pressurized nitrogen gas bottle, and then the back-away burn. This sequence is shown in Fig. 2, along with the nominal timeline of events. In the 4-hour time span between orbit departure and the Checkpoint burn, the onboard Natural Feature Tracking (NFT) software used surface images to estimate the spacecraft trajectory, which was then used to update the Checkpoint and Matchpoint burns to account for dispersions. During the descent to the surface, NFT was also used to assess the probability of making contact with known hazards, which would have triggered a wave-off burn if the probability of unsafe contact exceeded a certain threshold. [9]

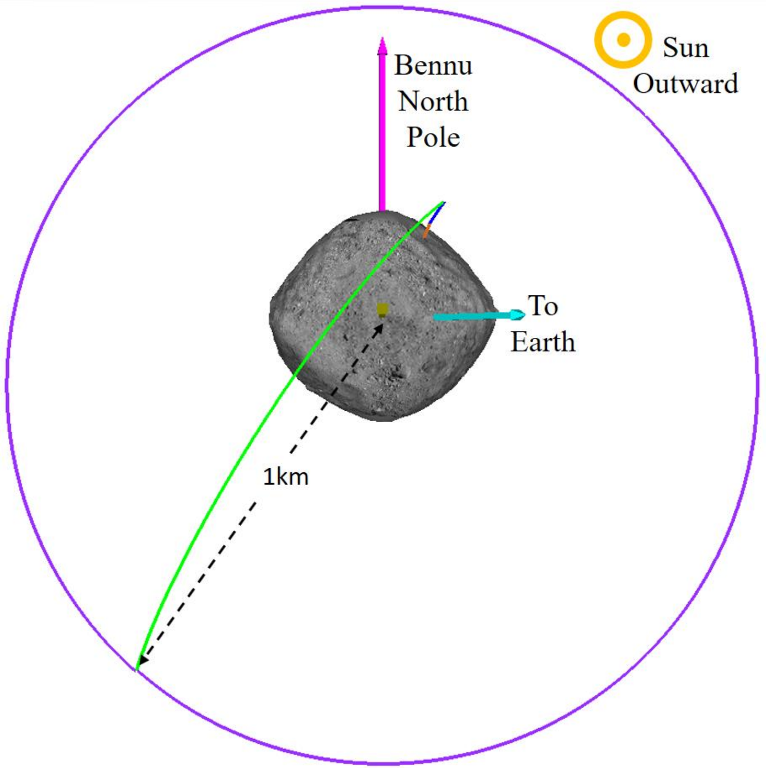

Fig. 1: Frozen Orbit (purple) and TAG Trajectory (green)

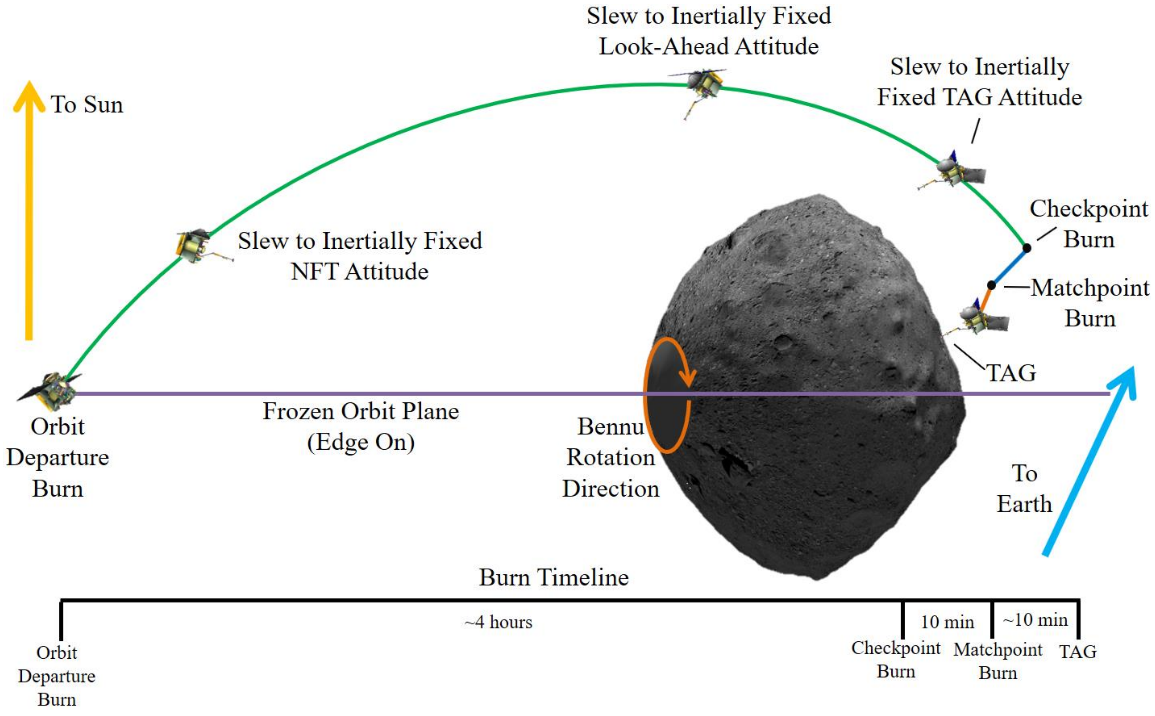

Fig. 2: TAG Sequence Viewed Along the Orbit Normal Vector after Orbit Departure

III. Hazard Map

The Bennu terrain is extremely rugged, as can be seen in the imagery of the Nightingale sample site shown in Fig. 3. This site was selected as the primary TAG site due to its abundance of fine-grained material and its relatively high probability of successful collection of at least 60 g of regolith (the mission level-1 requirement). [5] To safely contact the surface, our strategy was to identify all possible hazards around the site and enhance the onboard system to avoid those hazards.

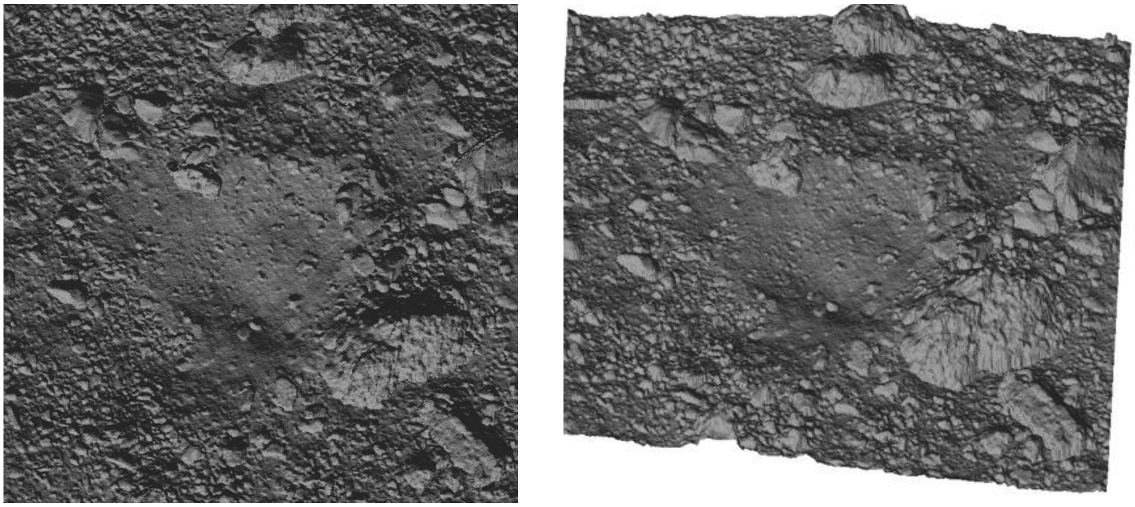

Fig. 3, TAG Site Image (left) and 3D surface model (right)

The sample collection hardware was designed to maintain contact with the surface for at least 5 seconds based on a 10 cm/s vertical velocity of the spacecraft. Over that time, it was expected that the spacecraft could tip-over by up to 25 degrees prior to the start of the back-away burn. The primary goal of the hazard map was to identify areas in the vicinity of the TAG site where the spacecraft could possibly make contact with a boulder or hill by tipping-over onto it or flying into it after the back-away burn. The diagram in Fig. 4 shows both types of hazards.

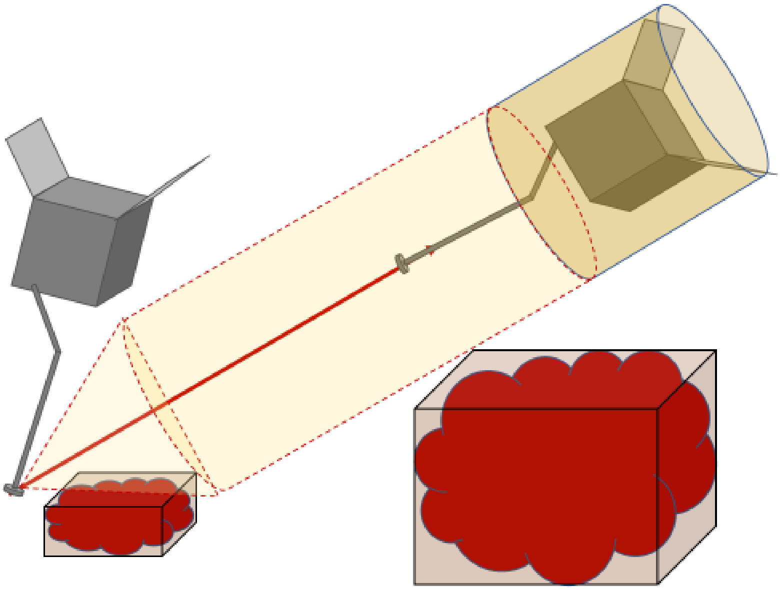

Fig. 4, Tip-Over and Back-Away Hazards

For every facet of the 3D surface model in the vicinity of the TAG site, the surrounding area was checked for possible hazards. If making contact at a given facet results in a tip-over or back-away hazard, the facet was colored red. Otherwise, the facet was colored green. This color-coded terrain model is shown in Fig. 5. Since this step in generating the hazard map is restricted to only assess tip-over and back-away hazards, the tops of hills and boulders are colored green, though we may not want to make contact there.

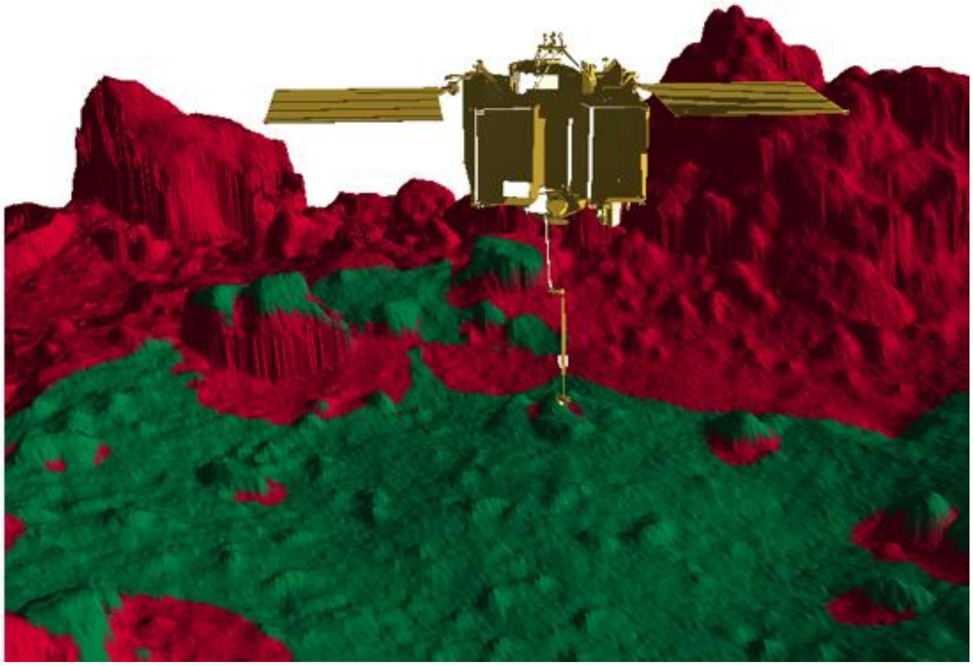

Fig. 5, TAG Site Terrain Color-Coded for Possible Hazards

The next step was to refine the hazard map to include areas where the spacecraft could slide from a green facet to a red facet during contact, and to include to tops of hills and boulders that the spacecraft could fall off of. In this step, we also reduced the resolution of the map being used onboard to allow it to make use of the existing DEM (Digital Elevation Map) already being used by NFT, and limited the safe area based on the TAG error analysis. Fig. 6 shows the two maps with the final version on the right.

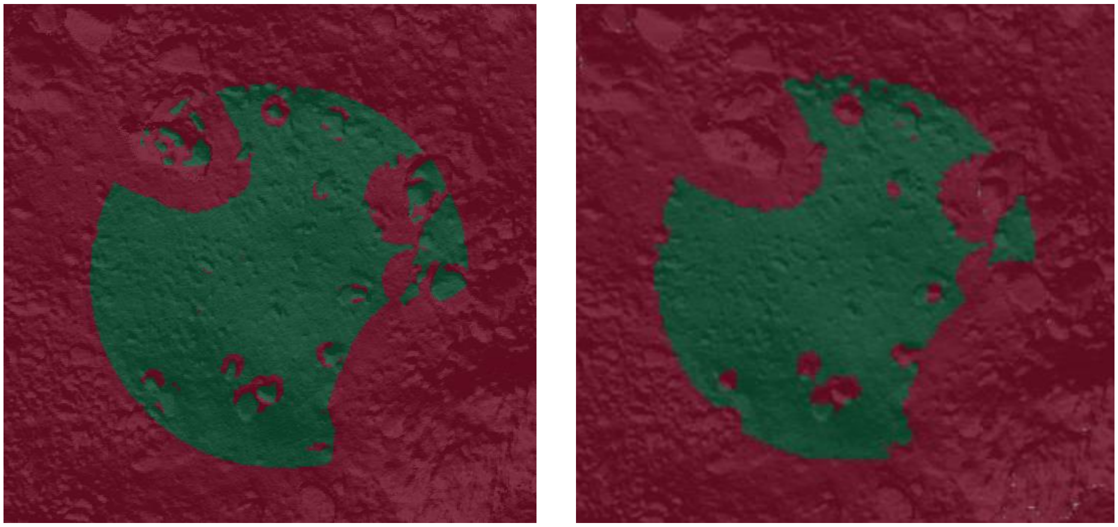

Fig. 6, Hazard Map Refinement

With the hazard map onboard the spacecraft, NFT performs a wave-off assessment during descent. The flight software takes NFT's predicted TAG position and covariance and integrates the corresponding 2-dimensional probability density function against the hazard map to determine the probability of unsafe contact. If that probability is larger than a configurable threshold, NFT would trigger a wave-off to protect the spacecraft, resulting in an early back-away burn at 5 m altitude. The wave-off threshold was chosen to be 15%, based on a mission requirement to ensure 99% safety which means that our probability of unsafe contact must be below 1%. [5] Combining the Gaussian distribution of TAG delivery errors with the residual probability of making contact with a red facet on the hazard map when we do not wave-off, the total probability of unsafe contact was 0.5%.

IV. Navigation and TAG Execution

The planning for the TAG event began 6 weeks in advance with the Preliminary (Prelim.) Design. The TAG Monte Carlo error analysis performed with the Prelim. Design values in Table 1, Table 2, and Table 3 showed that the maximum TAG position error was 6.8 m with a probability of wave-off of 5.8%. Fig. 7 shows the Preliminary TAG 3σ position error ellipse overlaid on the hazard map for the selected TAG site on the left. The red regions indicate possible hazards, the yellow regions indicate areas where the spacecraft would wave-off due to uncertainty in the onboard position estimate and proximity to the possible hazards, and the green regions are areas where the spacecraft could safely contact the surface. The X/Y axis in the upper right corner shows the spacecraft orientation at the time of TAG.

Table 1, Navigation State Uncertainty at Orbit Departure

	Position Uncertainty (m, 3σ)			Velocity Uncertainty (mm/s, 3σ)		
	Radial	Transverse	Normal	Radial	Transverse	Normal
Pre-Launch	12.5	52.6	3.80	3.92	0.506	0.0314
Prelim. Design	3.63	20.6	0.523	1.58	0.169	0.0785
Late Update	3.53	12.2	1.24	0.927	0.111	0.0783

Table 2, Maneuver Execution Errors

	Pre-Launch		Prelim. Design & Late Update	
	Magnitude Error	Transverse Error	Magnitude Error	Transverse Error
Orbit Departure	RSS(0.3mm/s, 1.5%ΔV)	0.3mm/s+2.5%ΔV	RSS(0.4mm/s, 0.0%ΔV)	0.0mm/s+1.3%ΔV
Checkpoint X	RSS(1.5mm/s, 5.0%ΔV)	1.5mm/s+10%ΔV	RSS(1.3mm/s, 4.4%ΔV)	0.0mm/s+3.0%ΔV
Checkpoint Y	RSS(1.5mm/s, 5.0%ΔV)	1.5mm/s+10%ΔV	RSS(1.3mm/s, 4.4%ΔV)	1.0mm/s+3.5%ΔV
Checkpoint Z	RSS(1.5mm/s, 5.0%ΔV)	1.5mm/s+2.5%ΔV	RSS(1.3mm/s, 4.4%ΔV)	0.5mm/s+1.4%ΔV
Matchpoint X	RSS(1.5mm/s, 5.0%ΔV)	1.5mm/s+10%ΔV	RSS(1.3mm/s, 4.4%ΔV)	1.0mm/s+3.0%ΔV
Matchpoint Y	RSS(1.5mm/s, 5.0%ΔV)	1.5mm/s+10%ΔV	RSS(1.3mm/s, 4.4%ΔV)	1.3mm/s+5.5%ΔV
Matchpoint Z	RSS(1.5mm/s, 5.0%ΔV)	1.5mm/s+2.5%ΔV	RSS(1.3mm/s, 4.4%ΔV)	0.0mm/s+1.2%ΔV

Table 3, NFT State Uncertainty at Checkpoint

	Position Uncertainty (m, 3σ)			Velocity Uncertainty (mm/s, 3σ)		
	Radial	Transverse	Normal	Radial	Transverse	Normal
Pre-Launch	3.0	3.0	3.0	3.0	3.0	3.0
Prelim. Design	1.0	1.0	1.0	1.0	1.0	1.0
Late Update	1.0	1.0	1.0	1.0	1.0	1.0

To begin the TAG sequence, the Navigation team needed to deliver the spacecraft to the orbit departure latitude as accurately as possible. [10] This was accomplished with a pair of small phasing burns placed at 7 days and 3 days prior to orbit departure using two 0.09 N thrusters. The delta-V magnitudes of these burns were of 1.0 mm/s and 0.5 mm/s, respectively, and the resulting orbit departure latitude was within 1 degree of our targeted value. [8]

The day before TAG, the navigation team delivered a final estimate of the orbit departure state and uncertainty, shown in the last row of Table 1. This was used to re-run the TAG Monte Carlo error analysis and deliver a new estimate in the “Late Update” shown in Fig. 7 on the right. The final maximum TAG position error estimate was 6.5 m with a probability of wave-off of 5.4%, which was consistent with the preliminary design with slight improvement due to improved navigation performance.

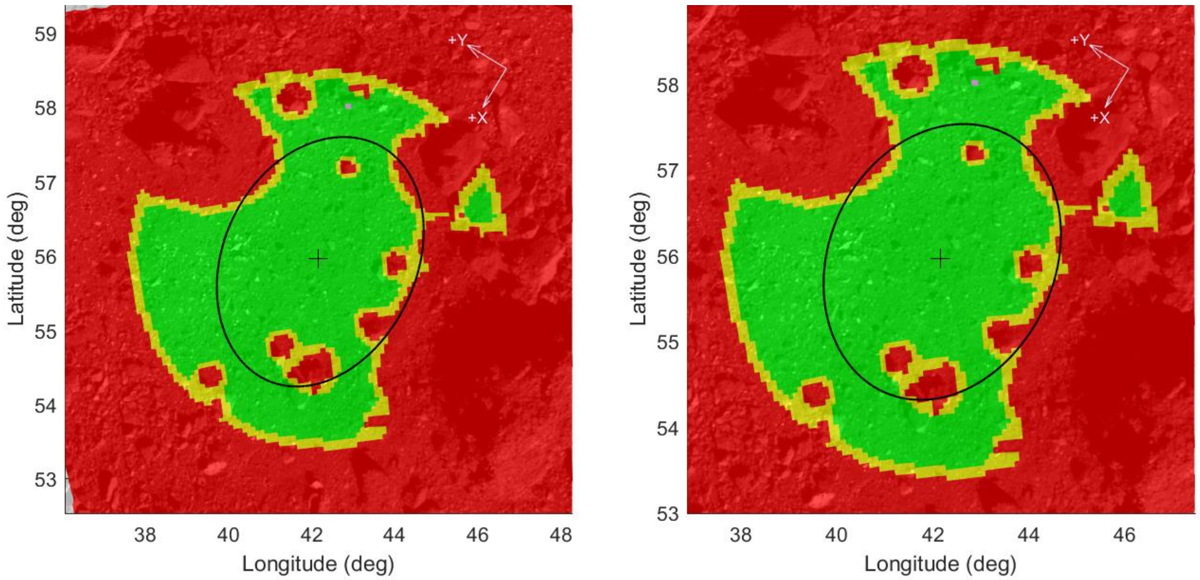

Fig. 7, TAG Delivery Error Ellipses: Left - Preliminary (6.8m max), Right - Late Update (6.5m max)

After the TAG event was complete and telemetry had been brought down to be processed, trajectory reconstruction showed that the spacecraft made contact with the surface within 1 m of the target. Fig. 8 shows the Late Update TAG error ellipse (in black) overlaid on the hazard map, with the addition of the onboard estimate of where the spacecraft would make contact for the wave-off assessment (in white), the last onboard state propagated to the surface (in blue), and the ground reconstruction of the trajectory (in magenta). All estimates are within one TAGSAM-head diameter of each other. The TAG position errors, along with the dimensions of the uncertainty ellipses, are provided in Table 4.

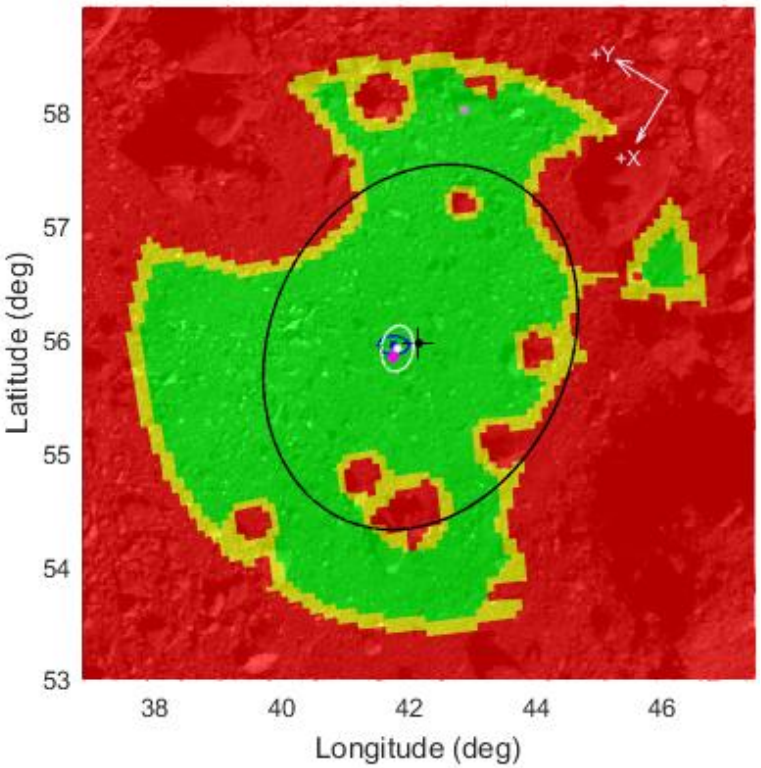

Fig. 8, Reconstructed TAG Position and Uncertainty

Table 4, Reconstructed TAG Position Errors

	Mean Error (m)	3σ Error Ellipse Semi-Major Axis (m)	3σ Error Ellipse Semi-Minor Axis (m)
Onboard Estimate for Wave-Off	0.74	0.783	0.537
Last Onboard State Estimate	0.85	0.514	0.316
Ground Reconstruction	0.98	0.150	0.146

V. Conclusion

The OSIRIS-Rex team was presented with a challenge upon arrival at Bennu. Through detailed analysis, enhancements to onboard processing, and precision navigation, we overcame that challenge and safely delivered the spacecraft to our chosen TAG site within 1 m of the target. Over a decade of effort culminated with the 0.3 m wide TAGSAM head making contact with the surface of Bennu for 6 seconds, as can be seen in the images in Fig. 9, collecting a regolith sample that will be returned back to Earth in 2023.

Fig. 9, Images of the Actual Sample Collection Event Taken Before Contact (left) and After (right).

References

[1] K. Berry, B. Sutter, A. May, K. Williams, B. Barbee, M. Beckman, W. Williams, "OSIRIS-REx Touch-And-Go (TAG) Mission Design and Analysis," Proceedings of the 36th Annual Guidance and Control Conference, 2013. AAS 13-095.

[2] K. Berry, P. Antreasian, M. Moreau, A. May, B. Sutter, "OSIRIS-REx Touch-And-Go (TAG) Navigation Performance," Proceedings of the 38th Annual Guidance and Control Conference, 2015. AAS 15-125.

[3] R. Olds, A. May, C. Mario, R. Hamilton, C. Debrunner, K. Anderson, "The Application of Optical Based Feature Tracking to OSIRIS-REx Asteroid Sample Collection." Proceedings of the 38th Annual Guidance and Control Conference, 2015. AAS 15-124.

[4] D. S. Lauretta, D. N. DellaGiustina et al., "The unexpected surface of asteroid (101955) Bennu." Nature 568, 55–60 (2019).

[5] K. Berry, K. Getzandanner, M. Moreau, P. Antreasian, A. Polit, M. Nolan, H. Enos, D. Lauretta, "Revisiting OSIRIS-REx Touch-And-Go (TAG) Performance Given the Realities of Asteroid Bennu," Proceedings of the 43rd Annual Guidance and Control Conference, 2020. AAS 20-088.

[6] D. S. Lauretta et al. "OSIRIS-REx at Bennu: Overcoming challenges to collect a sample of the early Solar System." In Sample Return Missions, ed. Longobardo, A. (Else-vier), pp. 163–194, 2021.

[7] D. R. Wibben, A. Levine, S. Rieger, J. V. McAdams, P. Antreasian, J. Leonard, M. Moreau, D. S. Lauretta, "OSIRIS-REx Frozen Orbit Design and Flight Experience," AIAA/AAS Astrodynamics Specialist Conference, 2019. AAS 19-677.

[8] Wibben, D.R., Levine, A., Rieger, S., McAdams, J.V., Antreasian, P., Getzandanner, K., Moreau, M., and Lauretta, D.S., "OSIRIS-REx Orbit Trim Strategy", Proceedings of the 2022 AAS/AIAA Space Flight Mechanics Meeting, 2022.

[9] R. D. Olds, C. J. Miller, C. D. Norman, C. E. Mario, K. Berry, E. Palmer, O. S. Barnouin, M. G. Daly, J. R. Weirich, J. A. Seabrook, C. A. Bennett, D. Lorenz, B. Rizk, D. S. Lauretta, "The Use of Digital Terrain Models for Natural Feature Tracking at Asteroid Bennu," Planetary Science Journal, in preparation.

[10] Leonard, J. M., Geeraert, J. L., Pelgrift, J. Y., Antreasian, P. G., Adam, C. D., Wibben, D.R., Getzandanner, K. M., Ashman, B. W., and Lauretta, D.S., "Navigation Prediction Performance During OSIRIS-REx Proximity Operations at (101955) Bennu", Proceedings of the 2022 AAS/AIAA Space Flight Mechanics Meeting, 2022.