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OSIRIS-REX TOUCH-AND-GO (TAG) MISSION DESIGN FOR ASTEROID SAMPLE COLLECTION

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The Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx) mission is a NASA New Frontiers mission launching in September 2016 to rendezvous with the near-Earth asteroid Bennu in October 2018. After several months of proximity operations to characterize the asteroid, OSIRIS-REx flies a Touch-And-Go (TAG) trajectory to the asteroid's surface to collect at least 60 g of pristine regolith sample for Earth return. This paper provides mission and flight system overviews, with more details on the TAG mission design and key events that occur to safely and successfully collect the sample. An overview of the navigation performed relative to a chosen sample site, along with the maneuvers to reach the desired site is described. Safety monitoring during descent is performed with onboard sensors providing an option to abort, troubleshoot, and try again if necessary. Sample collection occurs using a collection device at the end of an articulating robotic arm during a brief five second contact period, while a constant force spring mechanism in the arm assists to rebound the spacecraft away from the surface. Finally, the sample is measured quantitatively utilizing the law of conservation of angular momentum, along with qualitative data from imagery of the sampling device. Upon sample mass verification, the arm places the sample into the Stardust-heritage Sample Return Capsule (SRC) for return to Earth in September 2023.

I. MISSION OVERVIEW

OSIRIS-REx has five science objectives that are directly traceable to five Major Questions outlined in the NASA Solar System Exploration Roadmap and four Key Questions in the National Research Council New Frontiers in the Solar System document. The five scientific objectives of the OSIRIS-REx asteroid sample return mission are[1]:

- Objective 1: Return and analyze a sample of pristine carbonaceous asteroid regolith in an amount sufficient to study the nature, history and distribution of its constituent minerals and organic material.
- Objective 2: Map the global properties, chemistry, and mineralogy of a primitive carbonaceous asteroid to characterize its geologic and dynamic history and provide context for the returned samples.
- Objective 3: Document the texture, morphology, geochemistry, and spectral properties of the regolith at the sampling site in situ at scales down to the sub-centimeter.
- Objective 4: Measure the Yarkovsky effect on a potentially hazardous asteroid and constrain the asteroid properties that contribute to this effect.
- Objective 5: Characterize the integrated global properties of a primitive carbonaceous asteroid to allow for direct comparison with ground-based telescopic data of the entire asteroid population.

OSIRIS-REx will thoroughly characterize asteroid Bennu (Figure 1)[2,3]. Knowledge of the nature of near-Earth asteroids is fundamental to understanding planet formation and the origin of life. The return to Earth of pristine samples with known geologic context enables precise analyses that cannot be duplicated by spacecraft-based instruments, revolutionizing our understanding of the early Solar System. Bennu is both the most accessible carbonaceous asteroid and one of the most potentially Earth-hazardous asteroids known. As a Btype carbonaceous asteroid, Bennu represents an important source of volatiles and organic matter to Earth as well as being a direct remnant of the original building blocks of the terrestrial planets. Its properties (Table 1) have been well characterized by ground- and space-based telescopes in the visible, infrared, and radar, greatly reducing mission risk and providing strong evidence for the presence of regolith available for sampling. Its relatively Earth-like, low delta-V orbit is conducive for a low energy New Frontiers-level mission. Study of Bennu addresses multiple NASA objectives to understand the origin of the Solar System and the origin of life and will provide a greater understanding of both the hazards and resources in near-Earth space, serving as a precursor to future human missions to asteroids.

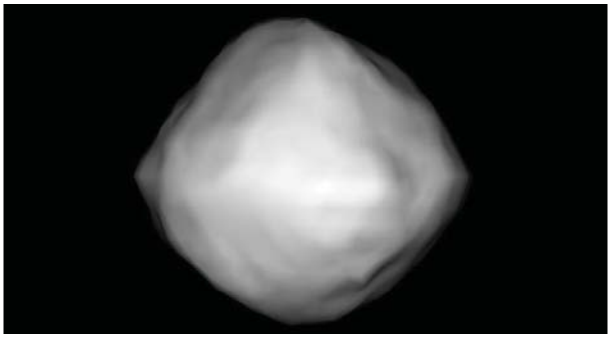

Fig. 1: Near-Earth Asteroid (101955) Bennu (shape derived from ground-based planetary radar data)

Properties	Nominal Value
Orbital Properties	
Semi-major Axis	1.126 au
Perihelion	0.897 au
Aphelion	1.356 au
Eccentricity	0.204
Inclination	6.035 deg
Longitude of Ascending Node	2.061 deg
Argument of Perihelion	66.223 deg
Mean Anomaly	101.704 deg
Orbital Period	436.6 days
Bulk Properties	
Mean Diameter	492 meters
Volume	0.0623 km^3
Surface Area	0.786 km^2
Bulk Density	1260 kg m^{-3}
Mass	7.8E+10 kg
Rotational Properties	
Rotation Period	4.297 hours
Direction of Rotation	Retrograde
Obliquity	176 deg
Pole Position	(45,-88) deg

Table 1: Bennu properties obtained through analysis of observations made with ground- and space-based telescopes

I.I Design Reference Mission (DRM)

The DRM timeline is summarized in Table 2, with the Earth range, Sun range, and Sun-Probe-Earth angle for the entire mission shown in Figure 2. OSIRIS-REx launches in September 2016, with a backup launch period occurring one year later. Following an Earth flyby and gravity assist in Sept 2017, OSIRIS-REx cruises for 11 months and starts the optical search for Bennu in Aug 2018, marking the beginning of the Approach phase. Rendezvous occurs in Oct 2018, followed by a month of slow approach to allow the flight system to search for moons around Bennu and to refine its shape and spin state models. Beginning with the Preliminary Survey and Orbital A phases in Nov 2018, OSIRIS-REx lays the foundation for navigating the spacecraft through the remainder of the encounter by estimating the mass of Bennu and transitioning from star-based to surface landmark-based optical navigation for precisely estimating the spacecraft's orbit state relative to the asteroid. OSIRIS-REx then performs comprehensive global mapping of the texture, mineralogy, and chemistry of Bennu in the Detailed Survey phase, resolving geological features, revealing its geologic and dynamic history, and providing context for the returned samples.

The five scientific instruments used to map the asteroid include the OSIRIS-REx Camera Suite (OCAMS), a suite of three cameras with fields of view of 0.8° (PolyCam), 4° (MapCam), and 21° (SamCam). MapCam also includes a set of four color filters for characterizing surface composition at visible wavelengths. The OSIRIS-REx Laser Altimeter (OLA) is a scanning lidar operating at 1µm used to map surface topography. The OSIRIS-REx Visible and Infrared Spectrometer (OVIRS) and Thermal Emission Spectrometer (OTES) map the surface composition from 0.4 - 50µm, and the Regolith X-ray Imaging Spectrometer (REXIS) provides an X-ray (0.3-7.5 keV) global map of the elemental abundance of Bennu.

The Orbital B phase, beginning in March 2019, establishes the "Safe Home" orbit at 1km radius from which all sorties closer to the surface begin, and by the end of this phase a set of four maps is produced to inform site selection from up to a dozen candidate sites. The Deliverability Map provides the level of accuracy that allows the Flight Dynamics to deliver the spacecraft to the desired location on the asteroid surface. The Safety Map provides an assessment of the chosen sample site to the spacecraft safety constraints. The Sampleability Map quantifies the probability that samples can be successfully collected based on grain size and distribution information. The Science Value Map depicts the probability that the collected sample contains organics and volatiles and can be placed in a geological context definitive enough to determine sample history. In the Reconnaissance phase, the instruments document the regolith at candidate sampling sites in situ at scales down to the sub-centimeter, providing the high-resolution information needed to confirm the presence of sampleable regolith and select the primary sample site. Following site selection, TAG rehearsals are conducted to demonstrate each step in the sample collection sequence prior to sending the flight system to the surface for sampling. In the Sample Collection phase OSIRIS-REx acquires a minimum of 60 g of bulk regolith and a separate 26 cm^2 of fine-grained surface material from Bennu.

The departure burn from Bennu occurs in March 2021, 931 days after arrival. On September 24, 2023, the SRC lands at the Utah Test and Training Range. Stardust heritage procedures are followed to transport the SRC to Johnson Space Center, where the samples are removed and delivered to the OSIRIS-REx curation facility. Analyses of these samples provide unprecedented knowledge about pre-solar history through the initial stages of planet formation to the origin of life.

Phase Name	Description	Start
Launch	Launch on an EELV from Cape Canaveral on an Earth-escape trajectory.	9/2016
Outbound Cruise	Perform deep space maneuver; Earth flyby & gravity assist; instrument calibration & checkout	10/2016
Approach	Perform braking maneuvers; survey the Bennu orbital environment for natural satellites; collect the first resolved images	8/2018
Prelim Survey	Estimate the mass of Bennu; refine shape and spin state models	11/2018
Orbital A	Demonstrate orbital flight; transition to landmark-based optical navigation	12/2018
Detailed Survey	Spectrally map the entire Bennu surface; collect images and lidar data for global shape and spin state models; search for dust plumes	1/2019
Orbital B	Collect lidar and radiometric data for high resolution topographic map and gravity model; observe candidate sampling sites and downselect for reconnaissance	3/2019
Recon	Conduct sorties for closer look at up to 4 candidate sampling sites and select 1	5/2019
TAG Rehearsal	Systematically and deliberately practice steps of sample collection sequence	8/2019
Sample Collection	Collect >60g (Level 2 requirement) of pristine bulk regolith and 26 cm^2 of surface material, and stow it in the Sample Return Capsule	9/2019
Quiescent Ops	Remain in Bennu's heliocentric orbit; monitor spacecraft health	10/2019
Return Cruise	Transport the sample back to the vicinity of the Earth	3/2021
Earth Return & Recovery	Get the sample safely to the ground and to the curation facility in late September 2023	7/2023

Table 2: OSIRIS-REx mission phases

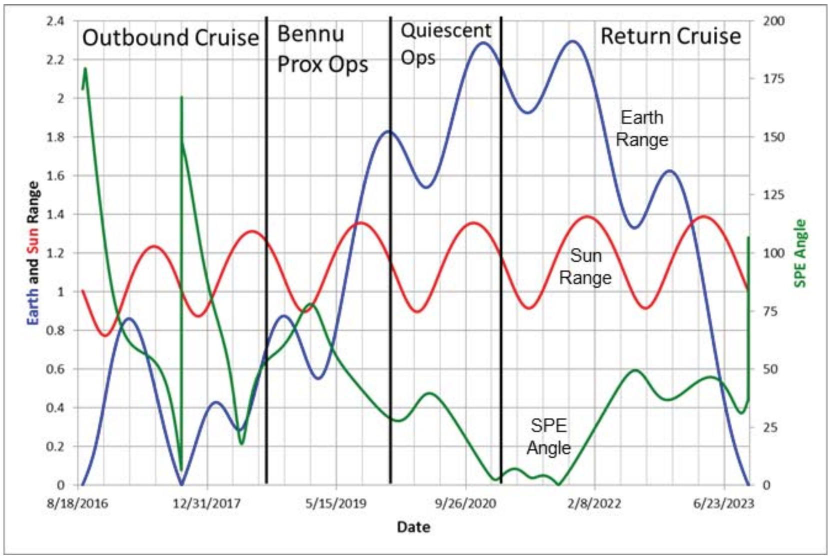

Fig. 2: Earth range, Sun range, and SPE angle from launch to Earth return

II. FLIGHT SYSTEM OVERVIEW

The OSIRIS-REx flight system is made up of the spacecraft bus (which includes the structure, and all of the various subsystem components to control and operate the vehicle), the touch and go sample acquisition mechanism (TAGSAM), the SRC, and the five science instruments (OCAMS camera suite, OVIRS and OTES infrared & thermal emissions spectrometers, OLA scanning laser, and REXIS X-ray instrument).

II.I Spacecraft (S/C) Overview

The spacecraft (Figure 3) is a derivative of the Mars Reconnaissance Orbiter (MRO) and Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft, leveraging the key heritage design components of these two missions. Healthy resource margins across the vehicle, fully redundant spacecraft subsystems with extensive cross strapping, and high heritage hardware enable flexibility throughout the spacecraft development and during flight operations.

Power

The power subsystem includes two rigid solar arrays, gimballed about the spacecraft Y and Z axes. In addition, two batteries are utilized for off-sun maneuvering, including the critical TAG mission phase.

Telecom

The telecom subsystem utilizes X-band communications, using a MAVEN build-to-print high gain antenna and MRO heritage traveling wave tube amplifier for science high data rate downlink. A medium gain antenna is utilized during the TAG mission phase. Also two low gain antennas are available for TAG but also used for nominal (and safe-mode) engineering data downlink and uplink commanding.

Propulsion

The high heritage propulsion subsystem is a single fault tolerant monopropellant system. The propulsion subsystem includes main engines, trajectory correction maneuver thrusters, attitude control system thrusters, and low thrust reaction engine assemblies.

Guidance, Navigation and Control (GN&C)

The GN&C subsystem includes four reaction wheel assemblies (RWAs) for performing spacecraft slewing and low jitter pointing during science operations. These reaction wheels also store system momentum between desaturation events. The GN&C subsystem is responsible for commanding all of the thrusters on the spacecraft including executing trajectory correction maneuvers and RWA desats. The GN&C subsystem utilizes an inertial measurement unit (IMU) and flight-proven star trackers to determine and propagate on-board attitude knowledge. Sun sensors additionally support spacecraft autonomous safing operations. Two GN&C sensors provide measurements used for relative navigation: a GN&C lidar is used for ranging to the surface to support TAG operations, and a TAG camera system (TAGCAMS) supports ground based navigation throughout proximity operations and autonomous on-board optical based navigation during the TAG phase.

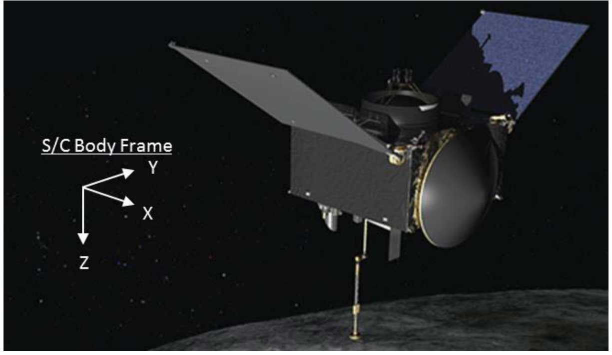

Fig. 3: OSIRIS-REx Flight System – Optimized for Asteroid Sample Return Mission.

II.II TAGSAM Overview

The TAGSAM is the key flight system component, used for making contact and acquiring sample from the surface of Bennu during the TAG mission phase. TAGSAM is designed to collect greater than 150 g to provide margin to the 60 g mission requirement. The TAGSAM functions by fluidizing regolith with high pressure gaseous nitrogen flow to transport it to a sample container. The TAGSAM is made up of a single planar, articulating arm with redundant motor windings at the shoulder, elbow, and wrist and provides large structural, torque, and alignment margins, ultimately ensuring successful sample acquisition and stowage of the TAGSAM head into the SRC (Figure 4).

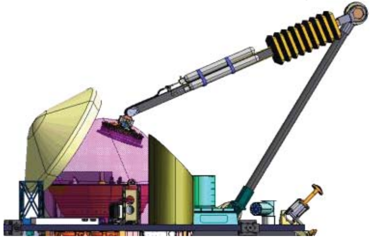

Fig. 4: Single Plane of Motion TAGSAM with potentiometers for simple & reliable positioning.

II.III SRC Overview

To safely return the collected sample to Earth, OSIRIS-Rex capitalizes on the success of NASA's Stardust mission. The proven Stardust SRC technology and capsule, mission operations, and mission design are all reused on OSIRIS-Rex for Bennu sample return.

III. TAG PHASE OVERVIEW

The TAG Phase has a set of driving requirements as listed in Table 3 to collect a sample and ensure spacecraft safety.

Key Driving Requirement	Capability
Collect > 150 g of Bulk Sample (Level 3 rqmt., provides margin to 60 g Level-2 mission rqmt.)	150-2000 g
TAG contact position error < 25m	< 22 m
TAG contact velocity error < 2cm/s	< 2 cm/s
Two or more contact detectors	IMU & Arm Microswitches
Onboard time of touch error < 8 sec	< 6 sec
Tip over < 45 deg during contact	< 35 deg
Escape maneuver after contact	Comply
Sample mass measurement accuracy < 90 g	< 49 g

Table 3: Key TAG requirements and capabilities.

The primary TAG activities include a set of three maneuvers to reach the surface: Orbit Departure, Checkpoint, and Matchpoint. This sequence targets the desired TAG site with the desired velocity at the correct time. Accurate position and velocity are crucial to ensure spacecraft safety and mission success.

An overall summary of all the TAG activities is shown in Figure 5. The clock starts ticking for the TAG phase timeline once the final RWA momentum desat is performed roughly 9 days before contact. This final desat prevents orbital perturbations as the Flight Dynamics team performs orbit determination and refines the maneuvers for TAG. Following the final desat, the sample mass measurement (SMM) procedure is executed to determine the baseline inertia of the sampler arm prior to collecting sample. By measuring the spacecraft inertia before and after collection, the collected mass can be measured as further described in section VII. After a few days of orbit determination, a very small (< 1 mm/s) phasing burn is performed to tweak the orbit and align OSIRIS-REx at the right place at the right time for the orbit departure maneuver.

NASA's deep space network (DSN) ground stations provide coverage for a high gain telecom pass to upload the final TAG sequence command blocks. This command upload includes all the details to allow the spacecraft to run autonomously to perform the maneuvers, allow onboard navigation and maneuver guidance updates, fault protection and safety corridor monitoring, contact detection and sample collection, and finally the backaway maneuver and recovery reconfiguration. Without this final command upload, the spacecraft would simply remain in the 1 km Safe Home orbit to allow the team to restart the TAG clock when ready.

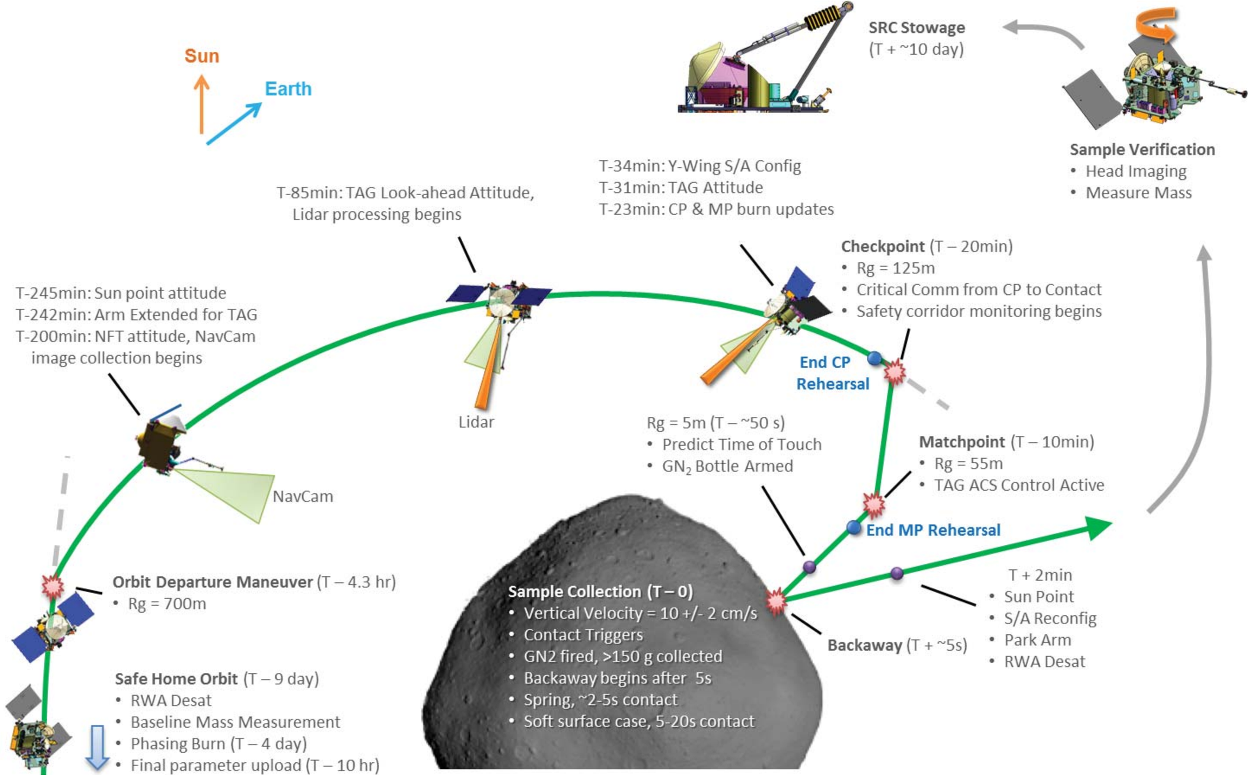

Fig. 5: TAG Phase Overview. The final four hours prior to contact are performed autonomously onboard, beginning with the orbit departure maneuver.

After the orbit departure maneuver, the spacecraft slews to an attitude to allow telecom coverage for ground to assess the burn performance. While the spacecraft has all necessary tools onboard to ensure safety, it is desirable for the ground to also monitor progress and safety. However, with a roundtrip light time of ~30 min, it is necessary for the spacecraft to be very robust at autonomously ensuring safety and not relying on ground intervention. While in this attitude the TAGSAM arm is moved into the sampling configuration using onboard potentiometer checks to verify final positioning.

The spacecraft then slews into an attitude to allow asteroid imaging with the NavCam (part of the TAGCAMS suite). These images support optical navigation both on the ground for reconstruction purposes as well as onboard the vehicle if necessary. The primary onboard navigation sensors for TAG are the redundant GN&C lidars. The lidar alone provides the necessary data to update onboard navigation, perform maneuver guidance, and monitor for range and rate safety to the surface. However, OSIRIS-REx has included onboard natural feature tracking (NFT) algorithms to process NavCam images as a backup to the lidar baseline. This offers two independent, onboard navigation techniques to meet all TAG requirements.

The lidar collects range data in the look-ahead inertial-fixed attitude and also in the final TAG inertial-fixed attitude as shown in Figure 5. Onboard processing determines the time that a configurable lidar range threshold is first crossed, providing in-track orbital knowledge. Lidar range measurements close to Checkpoint provide radial knowledge, and these two pieces of information go into a simple polynomial based algorithm to provide an update to the Checkpoint orbital state. The updated state is fed through a guidance algorithm to adjust the Checkpoint and Matchpoint burns to remove known trajectory dispersion and reduce the TAG contact position and velocity errors[4].

If NFT is used instead of lidar, the NavCam images that are collected are processed onboard to identify known surface features. The known features, as determined from ground tools utilizing a high accuracy asteroid shape model and the known TAG trajectory, are stored in a catalog and rendered onboard to represent their expected appearances. A correlation algorithm finds where the catalog features are in the images, and provides measurements to a Kalman Filter that estimates the orbital state of the spacecraft. The state estimate from NFT can be used with the same maneuver guidance algorithm to update the Checkpoint and Matchpoint burns.

Prior to the Checkpoint burn, the solar arrays are raised into the "Y-wing" configuration to minimize the chance of dust accumulation during contact, as well as provide more ground clearance in the case the spacecraft tips over (up to 45 deg) during contact. At this point, the spacecraft is in final TAG attitude and physical configuration ready for contact. If anything is determined out of bounds by the onboard fault protection, the spacecraft simply aborts the remaining TAG sequence and performs a backaway maneuver that escapes the asteroid's gravity (>0.5 m/s burn ensures escape) to allow ground to troubleshoot.

Upon Checkpoint burn completion, the onboard fault protection begins monitoring the approach state to ensure the spacecraft is within a safe corridor. Prior to Checkpoint, the spacecraft is on a passively safe trajectory and thus does not need to actively monitor range. Upon Matchpoint completion, the spacecraft attitude control system is set up to allow thruster control if the rates or position errors get above a deadband. This design helps mitigate unnecessary thruster firings prior to contact, thus reducing the likelihood of surface contamination from unreacted hydrazine. The design also provides the torque authority necessary to ensure spacecraft safety by not tipping over more than 45 deg.

All of the above activities are rehearsed prior to the actual TAG event. The Checkpoint Rehearsal demonstrates that the navigation and spacecraft configurations are achieved properly prior to the Checkpoint burn. The Matchpoint Rehearsal demonstrates the final two burns would have delivered OSIRIS-REx to the TAG site within the required accuracy. Each rehearsal takes three weeks to perform and evaluate before moving on to the next step. Thus, the system is very well characterized and understood prior to the actual TAG event. The slow orbital velocity of TAG provides these excellent rehearsal opportunities and ability to repeat events as necessary.

At 5m above the surface during the TAG event, as determined by either the lidar or NFT, the spacecraft arms the TAGSAM gas bottle pyro valve to fire upon contact declaration. Section VI describes the collection activities in more detail.

The TAGSAM arm spring assembly helps rebound the spacecraft from the surface while simultaneously keeping the head on the surface during the brief collection event. Depending on the asteroid surface properties, the contact event duration can be as short as 2 seconds or as long as 20 seconds. The spacecraft design has been rigorously analysed to support the wide variation in surface properties that will not be fully understood until we make contact.

Once contact is declared, a timer begins to allow for up to 5 seconds of collection before the backaway maneuver initiates to safely depart the asteroid. Immediately after the backaway completes, the spacecraft slews to a nominal sun attitude and reconfigures the solar arrays and sampling arm to allow power and thermal recovery.

After sufficient recovery time, the data collected during TAG by the various spacecraft sensors, cameras and science payloads is downlinked. Images during the full TAG sequence will greatly aid in understanding exactly where contact was made and the surface/regolith response to the sampling event. The spacecraft also provides important details on sensed accelerations to understand the surface contact dynamics. The ground operators then kick off a sequence to perform a stop burn to halt the drift away from the asteroid in case it's necessary to go back for a second sample attempt. If all goes as planned on the first attempt, then the spacecraft simply waits far away from the asteroid until it's time to head back to Earth.

To further assess TAG success, the spacecraft takes images of the sampler head to qualitatively determine if sample was collected, and performs the SMM procedure to measure change in inertia and quantitatively measure the collected sample mass. If sufficient sample is collected, then the sampler head is permanently stowed inside the SRC to complete the TAG phase.

IV. FLIGHT DYNAMICS OVERVIEW

Leading up to a TAG attempt, the spacecraft is in a 1km circular "Safe Home" orbit about the asteroid parallel to the Sun terminator plane. The orbit is designed to be slightly behind the Sun terminator plane so that the sunward component of the asteroid's gravitational pull counteracts the solar radiation pressure. This stable orbit allows for better prediction of the spacecraft state and removes the need for orbit maintenance.

Optical Navigation (OpNav) is performed using one of the redundant NavCams. During the mission phases prior to TAG, the entire asteroid surface is imaged and a full shape model is created. In the TAG phase, the OpNav process involves taking asteroid images from the terminator orbit and registering them to the asteroid model via ground processing. The registered images provide accurate measurement information that is used in the orbit determination process.

The spacecraft begins the TAG sequence in the Safe Home orbit, and the orbit departure latitude is chosen to be the negative of the TAG site latitude. A small maneuver (<1 mm/s) is used to adjust the phasing of the orbit to achieve the ideal time of orbit departure relative to the asteroid surface. When the spacecraft crosses the orbit departure latitude on the morning side of the asteroid, the orbit departure maneuver is performed with the goal of arriving at the 125 m altitude Checkpoint position 4 hours later. The trajectory sequence is depicted in Figure 5.

When the Checkpoint position is reached, the Checkpoint maneuver is performed to cancel out the majority of the surface-relative lateral velocity and begin descending towards the surface. The Checkpoint maneuver is performed to allow the spacecraft to maintain its inertial-fixed attitude.

After 10 minutes, the spacecraft reaches the Matchpoint at an altitude of 55 m. The Matchpoint maneuver reduces the rate of descent sufficiently to achieve a TAG vertical velocity of 10 cm/s. TAG occurs approximately 10 minutes after the Matchpoint maneuver.

The Flight Dynamics System has a requirement to deliver the spacecraft to within 25 m of a given TAG site with a Confidence Interval (CI) of 98.3%, which is approximately 2.85σ for a two dimensional Gaussian distribution. The 98.3% CI is an allocation of the overall mission-level requirement on the probability of successfully acquiring sufficient sample with a single TAG attempt. Three TAG attempts have been accounted for in the schedule, propellant budget, and TAGSAM gas bottles in case the first attempt is deemed unsuccessful.

The maximum vertical velocity has been designed to 12 cm/s to maintain spacecraft safety. TAG is targeted to occur with 10 cm/s of vertical velocity and is required to have less than 2 cm/s of vertical velocity error (3σ). This velocity requirement supports meeting the TAG positional accuracy requirements as well as the safety requirements.

There are two other TAG contact safety requirements that are levied on Flight Dynamics. One is the horizontal velocity error must be under 2 cm/s (3σ) to prevent additional tip over and loading concerns. The other is the TAG angle due to absolute time of contact error must be less than 4.4 deg (3σ) (~3 minutes). Because the TAG attitude is inertial-fixed, contact timing errors create spacecraft attitude errors relative to the surface as the asteroid spins at 1.4 deg/min.

Monte Carlo analysis is performed to determine expected TAG dispersions. Many contributing error sources are modelled including departure state errors, maneuver execution errors, lidar instrument bias and noise, surface roughness effects on lidar measurements, spacecraft attitude errors, gravity model errors, solar radiation pressure errors, and asteroid spin state errors. All of these errors are applied as zero-mean Gaussian. The following graphs (Figure 6) show the dispersions for a representative Monte Carlo run with error ellipses provided.

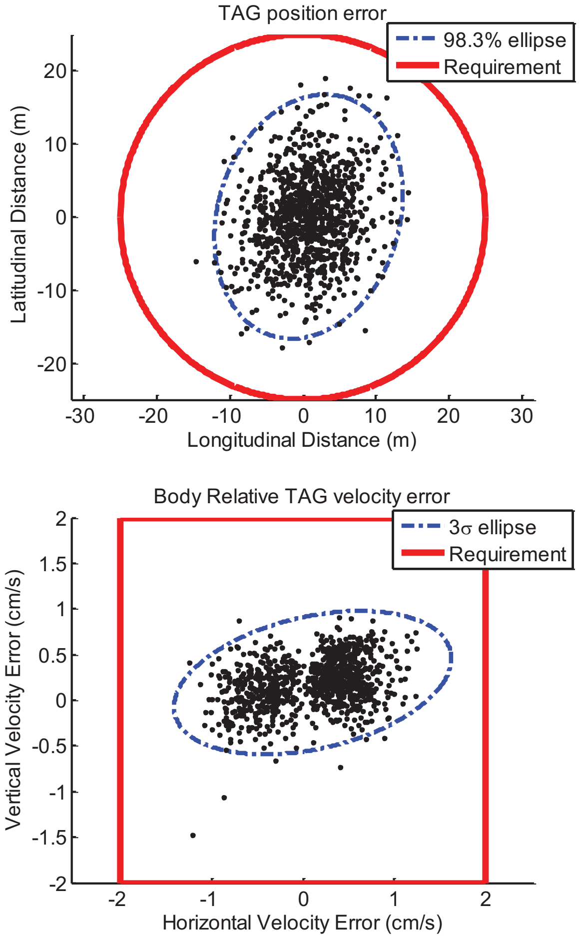

Fig. 6: TAG position and velocity errors fall within the allocated requirements.

V. TAG CONSTRAINTS

The spacecraft physical configuration and system performance has been designed to provide maximum flexibility in selection of the latitude, longitude, and altitude of the TAG site on the surface of Bennu. However, within this design space, analysis to evaluate the limits of performance has been undertaken (Figure 7). Mission requirements regarding telecom during critical events, landing site tilt accommodation, and flight hardware thermal safety have been identified and analysed across the surface of Bennu to provide insight into the relationship between the geographic and temporal variables. Results of this analysis are discussed briefly.

Detailed surface maps of the surface of Bennu do not currently exist, and will be generated during the Preliminary and Detailed Mapping phases of the proximity operations mission prior to selection of the TAG site. To ensure the spacecraft would have the ability to sample the most scientifically interesting region of Bennu, no assumptions on sampling latitude can be made prior to launch. Since Bennu is a retrograde rotator, with its North pole roughly perpendicular to the heliocentric plane, the only limitation on sampling latitude is driven by lighting requirements. The sampling site must be illuminated with at least a 5 degree elevation to provide optical images of the TAG event and the sampled surface. Given approximate latitude range of 85 degrees North to 85 degrees South, critical spacecraft performance has been evaluated for all epochs from the earliest possible TAG date up to asteroid departure in March 2021.

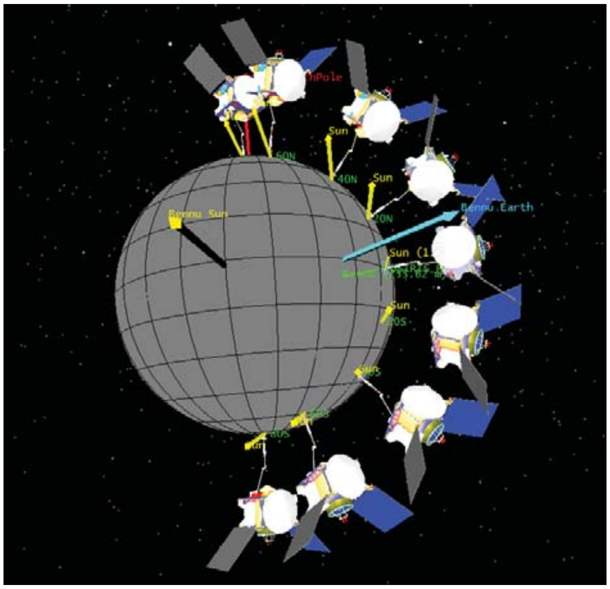

Fig. 7: Analysis performed across all Bennu latitudes to determine margin on all TAG constraints.

The low albedo of Bennu results in a surface that heats up rapidly from solar radiation soon after local sunrise. As a result, the ideal sampling site from a thermal perspective would be immediately after sunrise, before the surface temperature has had time to climb to unacceptable levels. Unfortunately, the relative placements of the Earth and Sun result in the Earth being below the horizon during much of the proximity operations timeline for early morning sampling locations. This would prevent a communications link during the TAG critical event period. Hence, TAG site location is placed on the opposite side of Bennu, closer to the sunset terminator, about 65 degrees from the local noon vector allowing for a modest surface cool down later in the afternoon. In general, this places the Earth in the zenith direction, as viewed from Bennu's equator. During the majority of the mission, the spacecraft places the sun within the spacecraft's XZ plane of symmetry with the sun always in the positive X direction. However, during TAG, this general philosophy is modified to place the Earth within the same XZ plane. To evaluate the ability of the flight system to maintain a communications link through either its Low Gain Antenna (LGA) or Medium Gain Antenna (MGA), the antenna offpoint margin was evaluated across the range of latitudes and possible sampling dates. The angular offpoint margin, defined as the amount of additional rotation the spacecraft can incur before the Earth moves past the 3dB limit of satisfying 40 bps, is shown in the following graphs (Figure 8).

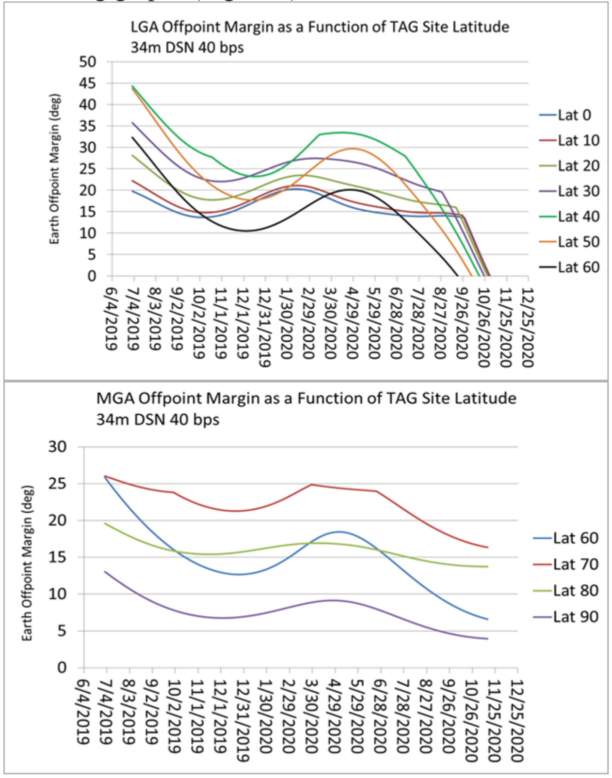

Fig. 8: Telecom off-point margin with 34m DSN for LGA (top) and MGA (bottom) provide flexibility for TAG site tilt accommodation.

It becomes apparent from this survey that for latitudes from 60 North to 60 South of the equator, 34m DSN critical event coverage can be satisfied using the LGA with at least 10 degrees of pointing margin until July 2020. Additionally, this offpoint margin can be considered a resource for sample site surface tilt accommodation. As long as a 3dB margin is maintained for communications, the spacecraft can align with various TAG site surface tilts for sampling. For latitudes beyond 60 degrees, critical event coverage requirements are best satisfied using the MGA. To provide for critical event coverage beyond July 2020, the mission has to use the 70m DSN, which provides pole to pole coverage, using the LGA, with greater than 10 degrees of offpoint margin, until Departure in March 2021. This data is reported in the following graph (Figure 9).

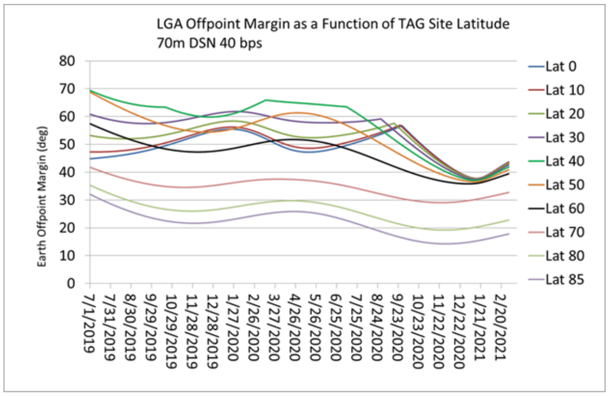

Fig. 9: 70m DSN offers TAG critical event coverage at all possible TAG dates and latitudes.

The thermal subsystem uses a combination of radiators and heaters to keep the spacecraft components within their operating ranges. The radiators on the negative Z side of OSIRIS REx are also protected from solar input by the addition of sun shields that keep the radiators shaded during the nominal sun pointed attitudes. However, as noted earlier, the TAG attitude is modified to place the Earth in the XZ plane, thereby allowing the solar vector to obtain a positive or negative Y component in the body frame. To analyse this, a parametric analysis was used to determine the worst case date and latitude configuration that would result in the maximum solar input into the thermal radiators. This worst case condition happens in early April 2020, at Bennu latitude of 60 North. Analysis demonstrates the thermal subsystem can satisfy requirements at this worst case date and latitude combination. All other dates and latitude combinations are less stressing and satisfy requirements with larger margins.

VI. SAMPLE COLLECTION

Lockheed Martin designed and developed TAGSAM, which will collect ≥ 150 g of pristine asteroid regolith for return to Earth. Sampling occurs by releasing pressurized nitrogen gas into the asteroid surface, and collecting the mobilized material. The pristine nature of the sample is maintained by the precision-cleaned TAGSAM head and the use of high-purity N2 gas. Over 10 years of extensive testing demonstrates TAGSAM collects the required sample mass from a variety of surface types and particle size-frequency distributions.

Contact with the surface and injection of pressurized gas into the surface will transfer kinetic energy to near-surface asteroid material. Because of the low-gravity environment at the asteroid, material will be accelerated to speeds that exceed the escape velocity of the asteroid, and some material may travel towards the spacecraft. Key components of the spacecraft are specifically oriented away from the surface during TAG (e.g. active side of the solar arrays, star trackers). Other key components are housed behind spacecraft structure or insulation blanketing, and so are not exposed to the TAG event. For components that remain exposed, we have completed extensive studies to estimate the amount, speeds, and risk of damage. While there is a possibility that asteroid material will contact parts of the spacecraft other than TAGSAM or the sampling arm, there is little risk to the health of the spacecraft because of the low encounter speeds, and acceptable levels of maximum possible dust mass loading.

VII. SAMPLE VERIFICATION & STOWAGE

The spacecraft utilizes the conservation of angular momentum to determine how much sample was collected, leveraging a technique demonstrated on the Cassini mission[5]. OSIRIS-REx gets high sensitivity on inertia measurement changes with the advantage of the long lever arm between the spacecraft CG and the sample location when in the configuration shown in Figure 10. The spacecraft spins 360 deg by driving the reaction wheels in the opposite direction, both before and after TAG. With known reaction wheel inertias, the necessary wheel speeds to reach the desired spacecraft spin rate enables solving for spacecraft inertia and ultimately the sample mass. Detailed error budgets and Monte Carlo simulations show the sample can be measured to an accuracy well within the 90 g peak-to-peak requirement.

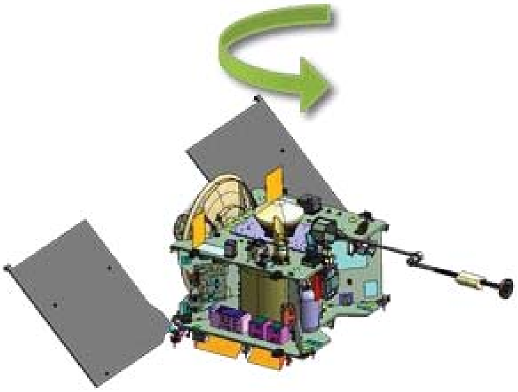

Fig. 10: Sample mass measured by performing 360 deg rotation with arm in two different configurations to determine delta inertia before and after TAG.

While sample mass is the key factor in determining if mission requirements were met, images of the sampler head during and after TAG will also help give confidence sample collection was successful. The sampler head design provides visibility into the collection chamber interior. Images are collected at various angles to inspect for any regolith on the surface as well as in the chamber (Figure 11). By design, regolith should not protrude from the sampler head to interfere with stowage. If images reveal unallowable protrusions, contingency procedures can remove them and ensure successful stowage.

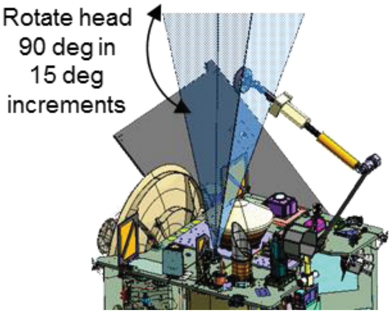

Fig. 11: Sampler head imaging performed with SamCam payload to inspect for collected sample.

Finally, when the sample is ready to be stowed, the SRC lid is opened to allow the sampler head to move into position above the SRC capture ring (Figure 12). The StowCam (part of TAGCAMS suite) and potentiometers verify alignments prior to sending commands to drive into the capture ring. Once captured, the sampler head cannot come out, so then the head is severed from the arm. The arm is then retracted into the launch configuration and the SRC lid is closed and latched for Earth Return.

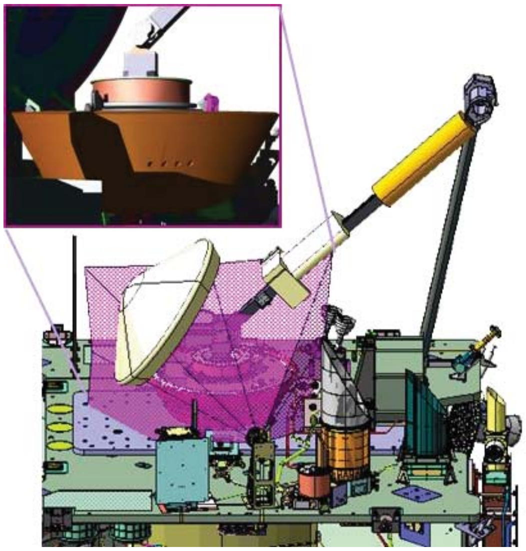

Fig. 12: Pre-stowage alignments and sampler head insertion to SRC capture ring imaged by StowCam.

VII. CONCLUSION

OSIRIS-REx is an exciting mission to collect and return to Earth a pristine, bulk sample of asteroid regolith. After an extensive remote sensing campaign, a TAG sample site is chosen and rehearsals are performed leading up to the final TAG event. Successful Flight Dynamics execution is critical to set the spacecraft on the proper initial trajectory for TAG, and then the autonomous systems onboard take over to update the final two maneuvers (Checkpoint and Matchpoint) and monitor performance to ensure safety through the collection event.

The flight system is robust for TAG by offering single fault tolerance across all subsystems and healthy margin on all key TAG requirements. Testing and analyses show that more than 150 g of material will be collected using TAGSAM, and measurements on orbit verify the collected sample mass via the SMM technique described. After mass verification, the sampler head is permanently inserted into the SRC and returns back to Earth in September 2023.

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