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The OSIRIS-REx Asteroid Sample Return:

Mission Operations Design

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I. THE OSIRIS-REX ASTEROID SAMPLE RETURN MISSION

A. Introduction:

NASA selected the OSIRIS-REx Asteroid Sample Return Mission as the third New Frontiers mission in May, 2011. The mission name is an acronym that captures the scientific objectives: **O**rigins, **S**pectral **I**nterpretation, **R**esource **I**dentification, and **S**ecurity–**R**egolith **Ex**plorer. OSIRIS-REx will thoroughly characterize near-Earth asteroid Bennu (Previously known as 1019551999 RQ36). This asteroid is both the most accessible carbonaceous asteroid and the most potentially hazardous asteroid known. Knowledge of its nature is fundamental to understanding planet formation and the origin of life. Only by understanding the organic chemistry and geochemistry of an asteroid sample can this knowledge be acquired.

OSIRIS-REx brings together all of the pieces essential for a successful asteroid sample return mission–The University of Arizona's (Tucson, AZ) leadership in planetary science and experience operating the Mars Phoenix Lander; Lockheed Martin's (Denver, CO) unique experience in sample-return mission development and operations; NASA Goddard Space Flight Center's (Greenbelt, MD) expertise in project management, systems engineering, safety and mission assurance, and visible-near infrared spectroscopy; KinetX's (Tempe, AZ) experience with spacecraft navigation; and Arizona State University's (Tempe, AZ) knowledge of thermal emission spectrometers. The Canadian Space Agency is providing a laser altimeter, building on the strong relationship established during the Phoenix Mars mission. In addition, MIT and Harvard College Observatory are providing an imaging X-ray spectrometer as a Student Collaboration Experiment. The science team includes members from the United States, Canada, France, Germany, Great Britain, and Italy.

B. Science Instrumentation:

OSIRIS-REx delivers its science using five instruments and radio science along with the Touch-And-Go Sample Acquisition Mechanism (TAGSAM). All of the instruments and data analysis techniques have direct heritage from flown planetary missions.

TAGSAM is an elegantly simple device that satisfies all sample-acquisition requirements. TAGSAM consists of two major components, a sampler head and an articulated positioning arm. The head acquires the bulk sample by releasing a jet of high-purity N_2 gas that "fluidizes" the regolith into the collection chamber. The articulated arm, which is similar to, but longer than, the Stardust aerogel deployment arm, positions the head for collection, brings it back for visual documentation, and places it in the Stardust-heritage Sample Return Capsule (SRC).

The OSIRIS-REx Camera Suite (OCAMS) is composed of three cameras. PolyCam provides long-range Bennu acquisition and high-resolution imaging of Bennu's surface. MapCam supports **optical navigation** during proximity-operations, global mapping, and sample-site reconnaissance. SamCam performs sample-site characterization and sample-acquisition documentation.

The OSIRIS-REx Laser Altimeter (OLA) provides high-resolution topographical information [1]. OLA's high-energy laser transmitter is used for ranging from 1–7.5 km that supports Radio Science and provides scaling information for images and spectral spots. OLA's low-energy transmitter is used for rapid ranging and LIDAR imaging at 500 m to 1 km, providing a global topographic map of Bennu as well as local maps of candidate sample sites.

The OSIRIS-REx Visible and Infrared Spectrometer (OVIRS) is a linear-variable point spectrometer (4-mrad FOV) with a spectral range of 0.4 – 4.3 µm, providing full-disk Bennu spectral data, global spectral maps (20-m resolution), and local spectral information of the sample site (0.08 – 2-m resolution). OVIRS spectra will be used to identify volatile- and organic- rich regions of Bennu's surface and guide sample-site selection.

The OSIRIS-REx Thermal Emission Spectrometer (OTES) is a Fourier-transform-interferometer, point spectrometer (8-mrad FOV) that collects hyper spectral thermal infrared data over the spectral range from 4 – 50 µm with a spectral resolution of 10 cm^{-1}. OTES provides full-disk Bennu spectral data, global spectral maps, and local sample site spectral information.

The Regolith X-ray Imaging Spectrometer (REXIS) Student Collaboration Experiment is a joint venture of Massachusetts Institute of Technology and Harvard-Smithsonian Center for Astrophysics. REXIS significantly enhances OSIRIS-REx by obtaining a global X-ray map of elemental abundance on Bennu.

Radio Science will determine the mass of Bennu and estimate the mass distribution to 2nd degree and order, with limits on the 4th degree and order distribution. Knowing the mass estimate and shape model, the team will compute the bulk density and apparent porosity of Bennu. These data are obtained by combining radiometric tracking data with optical observations, supplemented by OLA altimetry data. Together, this information constrains the internal structure. Most importantly, the gravity field knowledge provides information on regolith mobility and identifies areas of significant regolith pooling.

II. OSIRIS-REx Asteroid Operations Activities

A. Mission Timeline:

The OSIRIS-REx mission employs a methodical, phased approach to ensure success in meeting the mission's science requirements. OSIRIS-REx launches in September 2016. Sampling occurs in 2019 and departure burn from Bennu occurs in March 2021. On September 24, 2023, the SRC lands at the Utah Test and Training Range (UTTR). 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. After a six-month preliminary examination period the mission will produce a catalog of the returned sample, allowing the worldwide community to request samples for detailed analysis.

The mission philosophy is to move closer to the asteroid in measured steps. This section focuses on the measured steps to encounter Bennu.

B. Approach

During approach OSIRIS-REx will optically acquire Bennu, search for natural satellite hazards, and perform initial characterization of Bennu. PolyCam will optically acquire Bennu and transmit images to refine the asteroid's ephemeris. MapCam will then search the 31 km-radius Hill Sphere for natural satellites around RQ36, and will characterize the object(s) to assess the hazard these objects pose. As the spacecraft approaches Bennu, OSIRIS-REx will collect progressively higher resolution images to construct a shape model and identify landmarks for navigation (Figure 1).

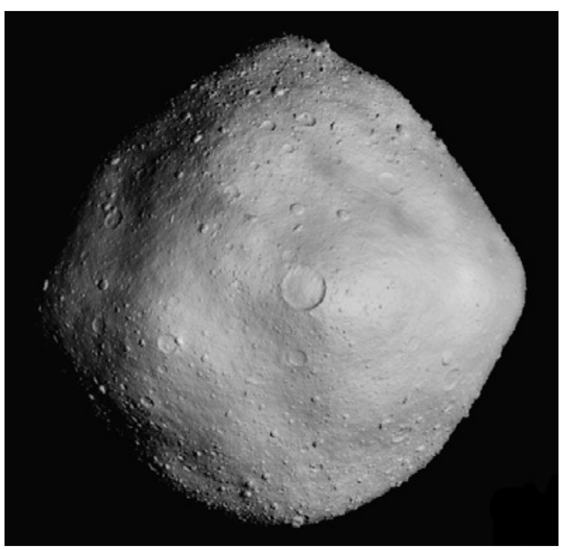

Figure 1 Simulated asteroid image—topography overlaid by Robert Gaskell of PSI on radar imagery of Bennu. Credit: NASA/GSFC/UA.

C. Survey

Survey contains the DRM phases Survey through reconnaissance (figure2). Survey will provide the first detailed measurement of Bennu's position and refine the size and rotation of Bennu for the navigation plan. MapCam will search for small particle plumes that would indicate volatile outgassing, a potential spacecraft hazard. Based on PolyCam, MapCam, OLA, OTES and OVIRS data, the science team will produce maps of Bennu's surface and identify potential sample sites. In parallel, the spacecraft team will acquire detailed gravity field data using Radio Science (radiometric ranging and Doppler tracking using the Deep Space Network), which will be used for proximity operations.

D. Sample Collection

OSIRIS-REx will touch the surface of Bennu to collect a sample and then back away (Touch-and-Go (TAG)). Given the one-way light time of 15-20 minutes, the spacecraft team will require on-board guidance and navigation to perform the TAG operation. OSIRIS-REx will use range measurements to constrain the spacecraft position relative to Bennu and then autonomously adjust the maneuvers to contact the surface in the sample site area. Sensing of surface contact by the spacecraft will trigger the activation of the sampling mechanism to collect regolith. The spacecraft will then back away from Bennu at faster than the surface escape velocity of approximately 20cm/s. Once the OSIRIS-REx spacecraft is at a safe distance, the team will stow the sample in the Sample Return Capsule (SRC).

E. Earth Return and Reentry

As OSIRIS-REx approaches Earth, the plans for reentry are reviewed 6 months before arrival, and preparations begin. The S/C performs approach TCMs to precisely align with the entry path and target minimum altitudes 200 km above Earth. The SRC is released 4 hours prior to atmospheric entry interface and, 30 minutes later, the Earth deflection maneuver raises the S/C perigee to 250 km altitude leaving the S/C in a 1.0 by1.9 AU solar orbit that will not re-intercept Earth.

The S/C has completed its mission and is configured to safe hold for possible future use. The SRC enters the atmosphere at a nominal entry that avoids any major population centers in the event of an unrecoverable S/C failure. The SRC freefalls through the atmosphere for 8 minutes until approximately 36-km altitude at which point the parachute deployment sequence is initiated.

It is tracked with UTTR range radars. A UHF beacon once located, the SRC is recovered and transported to the JSC Space Exposed Hardware cleanroom. The sample canister is opened in the dedicated OSIRIS-REx curatorial facility at JSC for documentation, preliminary examination, distribution to the worldwide analytical community, and archiving for future generations.

III. Mission Operations Design Guiding Principles

In order to succeed with this unique mission we took a very conservative approach to mission operation using best practices in designing mission operations:

1. A Design Reference Mission (DRM) that ties together space craft, instrument and operations scenarios.
2. Time is a critical asset: the project changed the asteroid arrival date, to arrive one year earlier, and to provided additional time margin
3. Navigation is key to success. The mission is dependent upon optical navigation. A dedicated wide angle Navigation camera and Independent on-board land mark identification software were added post-PDR
4. Planning and analysis tools: OSIRIS-REx is using a variety of tools to demonstrate that the DRM is achievable. STK is used for Mission Design and STK/Solis for instrument coverage analysis.
5. The project implemented lessons learned from other "small body" missions: APL/NEAR, JPL/DAWN and ESA/Rosetta.
6. Testing and readiness: Each key phase is planned carefully, tested and reviewed.
7. Conduct element peer reviews and ground systems reviews starting at SRR.

The remainder of the paper will further describe in further details the implementation of these best practices

A. Design Reference Mission (DRM)

The DRM serves as a configuration controlled baseline that ties all mission elements together and focuses the entire mission team on successfully collecting and returning the sample. Figure 2 described the ISRIS –REx phases.

The DRM was developed in the project proposal as the tool to demonstrate the project's methodical approach to collecting and returning an asteroid sample. Additionally the DRM serves as a high fidelity mission design and science operations plan by identifying daily spacecraft activities, science observations, optical navigation, data volume, and DSN contacts. This level of detail enables the project to implement a low risk operations strategy. In particular, ample proximity operations time is allotted to carefully characterize and study Bennu.

The DRM has gone through several revisions because the methodical approach of laying out daily activities has presented opportunities to lower risks through both spacecraft design changes and operations implementation. One example is the incorporation for human factors that had previously been overlooked.

Mission Phase Descriptions

PHASE	DESCRIPTION	START
Launch	Launch on an EELV from Cape Canaveral on an Earth-escape trajectory	9/4/2016
Outbound Cruise	Perform deep space maneuver; Earth flyby & gravity assist; instrument calibration & checkout	10/5/2016
Approach	Obtain Bennu optical; perform braking maneuver; survey the Bennu orbital environment for natural satellites; obtain the first resolved images	8/17/2018
Preliminary Survey	Estimate the mass of Bennu; refine shape and spin state models	11/12/2018
Orbital A	Demonstrate orbital flight; transition from star field-based to surface landmark-based optical navigation	11/22/2018
Detailed Survey	Spectrally map the entire Bennu surface; collect images and LIDAR data for global shape and spin state models; search for dust plumes	12/14/2018
Orbital B	Collect LIDAR and radiometric tracking data for high resolution topographic map and gravity model; observe up to 12 candidate sampling sites and down select to 4 for reconnaissance	2/7/2019
Reconnaissance	Conduct sorties for a closer look at up to 4 candidate sampling sites and down select to 1	3/18/2019
Rehearsal	Systematically and deliberately practice each step in the sample collection maneuver	6/24/2019
Sample Collection	Collect >60g of pristine RQ36 bulk regolith and 26 cm2 of surface material, and stow it in the Sample Return Capsule	7/22/2019
Quiescent Operations	Remain in Bennu's heliocentric orbit; monitor spacecraft health	8/21/2019
Return Cruise	Transport the sample back to the vicinity of the Earth	3/3/2021
Earth Return & Recovery	Get the sample safely to the ground and to the curation facility in late September 2023	7/24/2023

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Figure 2 Design reference mission

B. Time as Asset

Originally the mission had 425 days from the start of the Bennu approach on October 16, 2019 with departure on March 4, 2020. The selected Launch Vehicle provided more lift capability than the proposal, which allowed arriving to asteroid 505 days earlier. The current plan is to approach Bemmu at August 2018 and departing March 4 2020. We collect the sample within the first 412 days which leaves the project with an additional 518 for contingencies.

C. Navigation is Key

Navigation around the Asteroid requires more accuracy than conventional tracking radiometric. Using stereophotoclinometry (SPC) the science team will define the Asteroid shape. FDS will be using a dedicated navigation camera; that was added after PDR, for landmarks tracking. FDS determined that the required navigation accuracies could not be met just by using the OCAMs camera suite the DRM helped identify conflicts between science and navigation.

The Touch and Go (TAG) maneuver is carefully designed by FDS providing a Departure, Check Point, and Match Point maneuvers while the SC provides corridor control to sample the asteroid. (2). Figure 3 describe TAG steps with navigation match and check points.

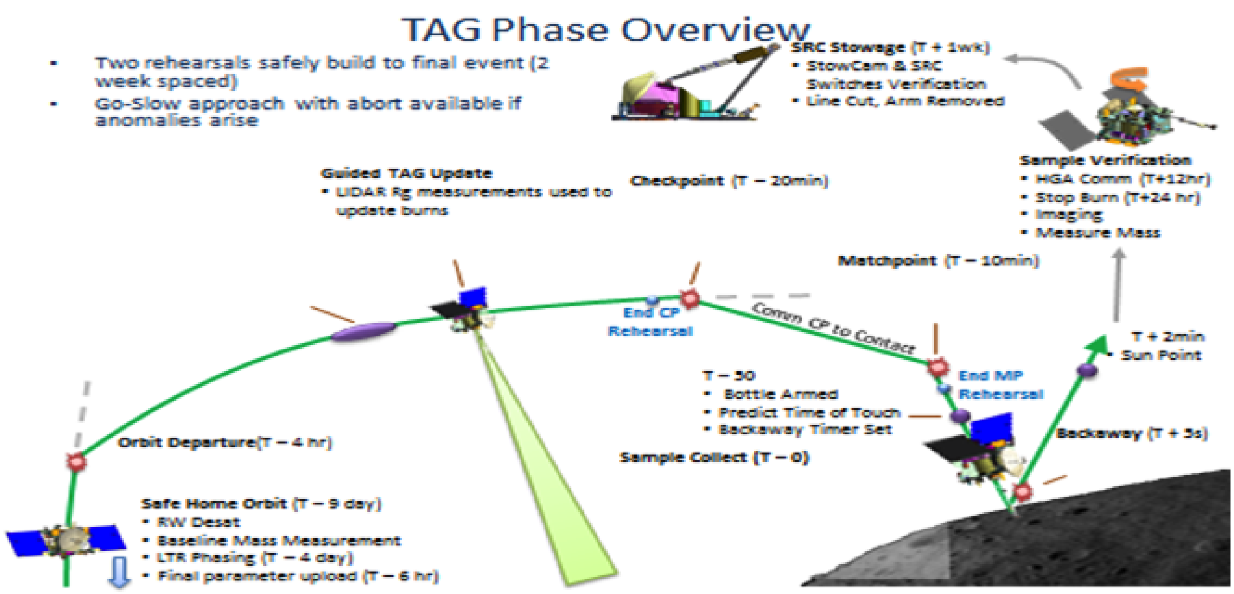

Figure 3 Touch and Go (TAG) design

D. Planning and Analysis Tools

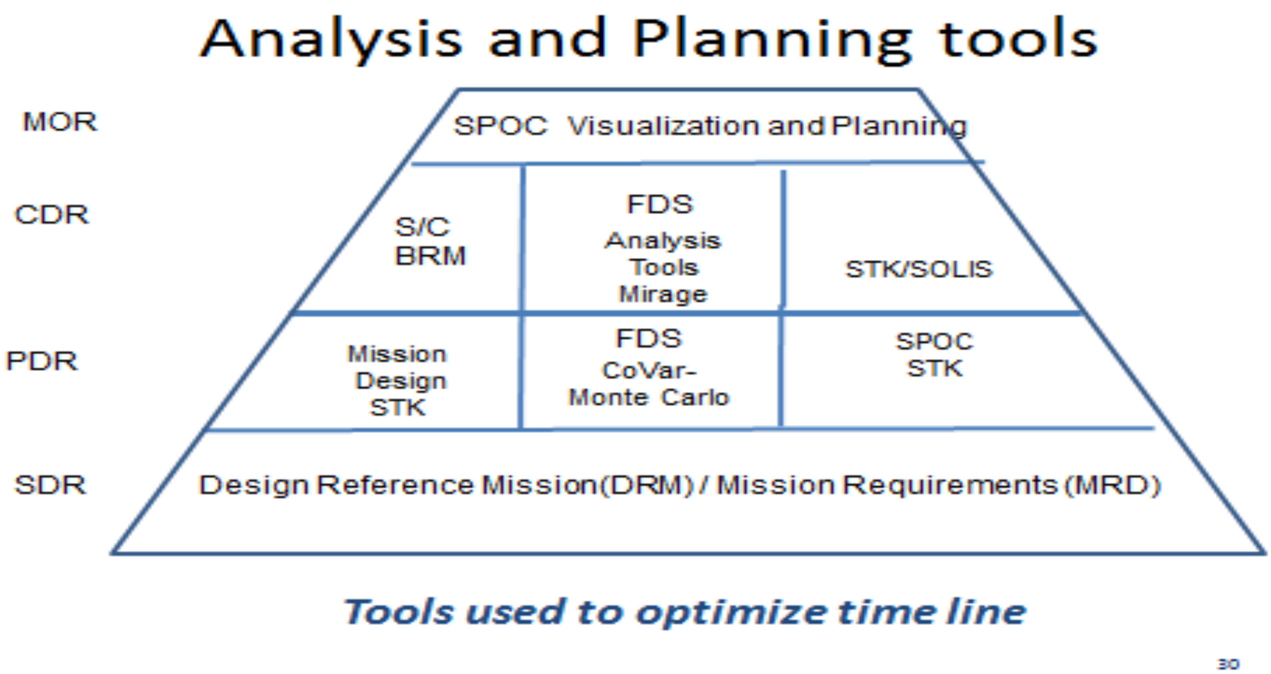

Figure 4 Analysis and planning tool implementation

The DRM is controlled by Mission System Engineering. The Ground, Mission Design and Spacecraft Design Teams were required to demonstrate the DRM is achievable. The Mission Design team used STK to design trajectory for each DRM phase. The Spacecraft Design team developed a Baseline Reference Mission (BRM). The BRM identified thermal and HGA constraint that were fed back into the time line to further ensure the DRM can be performed.

The Science Team is using STK/SOLIS. The Science Team added instrument views and analyzed science instrument activities, using the trajectories provided by Mission Design Team. STK/SOLIS supports SC constraints. The next analysis of STK/SOLIS, will integrate trajectory, spacecraft and instrument activities and thus increase the confidence that DRM is achievable.

To support the details of command generation and minute by minute activities a planning system is being implement. The planning system selected is MRO heritage developed by University of Arizona. The Planning tool is integrated with the OSIRIS-REx Visualization tool (J-Asteroid by ASU), STK/SOLIS. Figure 4 summerze the implaementation of OSIRIS-REx ananlysis and palning tools stategy.

Key to success of ground systems is a well-defined interface between ground elements: Mission Control (MSA), Flight Dynamics and Science. The team is capturing the entire interface in the CORE system engineering tool. The ground team will be testing these interfaces in a series of Ground Readiness Tests (GRT).

E. Lessons Learned

During the proposal phase the project implemented a DRM based on NEAR, Stardust and Hayabusa experiences. This led to using a methodical phase approach and low risk operations. At any point we can stop and go back to previous step.

Upon start of phase B the team visited with a number of small bodies missions: Dawn, APL and Rosetta. Dawn and APL emphasized the importance of implementing a planning process early in the life cycle. We visited with ESA twice. During the first visit ESA emphasized the need for an independent Navigation camera. That recommendation was incorporated into spacecraft design after PDR. Our last visit to ESA emphasized the use of human “friendly” colander. The idea is to prevent personal “burn out” which has been implemented.

Another practice is shadowing other missions. OSIRIS REx ground personnel also shadowed MAVEN since CDR through its successful launch in November 2013.

The project is planning meetings with the Japanese sample return mission (Haybusa 1 and 2).

F. Testing and Readiness

In addition to launch campaign, OSIRIS-REx has the following key activities: Asteroid science and site selection, Touch and Go (TAG) and Earth Return. For each of these major activities a set of test are conducted throughout the mission life time. Starting with the ATLO System Verification Tests (SVT)that demonstrates the flight-like sequences using flight. During the operation phase (post launch) Operations Readiness Test (ORT) will be conducted for the Bennu science phase, TAG, and SRC Release. The ORTs will be followed by a Critical Event Review (CERR). In addition to ORT the Touch and Go will have two rehearsals where the entire activity will be rehearsed (without activating the gas).

G. Follow the Review Process

The ground segment instituted a rigorous review plan. Each element conducts an Engineering Peer Review culminated by Ground reviews for SRR, PDR and CDR. Typically proposals selected for implementation are not required to have a system definition review (SDR). The OSIRIS-REX ground segment held both a ground and science processing SDR. For the Ground System PDR we held an Operation/Cadence, Flight Dynamics and Science processing Engineering peer review. The science team was reviewd as part as Scince Processing and operations center (SPOC) reviews.
In preparation for Critical Design Review, in addition to element reviews, we held a Touch and Go (TAG) engineering peer review and a verification and validation (V&V) technical interchange.

Summary

Planning for OSIRIS-REx successful mission operations is a continuous effort. Best practices are continuously being used. Analysis and planning tools used in Phase C-D will be the basis for detailed planning during phase E.

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