The OSIRIS-REx Asteroid Sample Return Mission Operations Design

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1 Abstract

OSIRIS-REx is an acronym that captures the scientific objectives: Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer. OSIRIS-REx will thoroughly characterize near-Earth asteroid Bennu (Previously known as 1019551999 RQ36).

The OSIRIS-REx Asteroid Sample Return Mission 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.

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, with a backup launch period occurring one year later. Sampling occurs in 2019. The departure burn from Bennu occurs in March 2021. On September 24, 2023, the Sample Return Capsule (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.

Traveling and returning a sample from an Asteroid that has not been explored before requires unique operations consideration. The Design Reference Mission (DRM) ties together spacecraft, instrument and operations scenarios. Asteroid Touch and Go (TAG) has various options varying from ground only to fully automated (natural feature tracking). Spacecraft constraints such as thermo and high gain antenna pointing impact the timeline. The mission is sensitive to navigation errors, so a late command update has been implemented. The project implemented lessons learned from other “small body” missions. The key lesson learned was “expect the unexpected” and implement planning tools early in the lifecycle.

This paper summarizes the ground and spacecraft design as presented at OSIRIS-REx Critical Design Review(CDR) held April 2014.

2 THE OSIRIS-REX ASTEROID SAMPLE RETURN MISSION

2.1 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.

2.2 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 2^{nd} degree and order, with limits on the 4^{th} 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.

3 OSIRIS-REx Asteroid Operations Activities

3.1 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. Each of the following campaigns has a mission lead.

3.2 Navigation Campaign

The purpose of the Navigation Campaign is for the Navigation team to establish asteroid shape module, Mass Gravity and Optical landmarks. This campaign has three phases, Approach, Preliminary Survey, and Orbital A. The campaign concludes when the transition from star-based to optical-based navigation takes place.

During the Approach phase 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 Bennu and characterize the satellite(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).

Following approach the team will perform the Preliminary Survey phase which is a series of slow survey passes across the sunlit side of Bennu and over both poles with a 7 km closest approach. These hyperbolic flybys will provide the initial mass estimate to 1 % that enables the Navigation team to plan the maneuvers to enter orbit.

Following Preliminary Survey the spacecraft will enter into a 1.5 km orbit so the Navigation team can transition from star based to landmark optical tracking for the remainder of Bennu operations. Additionally, while in orbit, detailed science data is collected to start the search for a sample site.

Figure 1 Simulated asteroid image—topography overlaid by Dr. Robert W. Gaskell | Planetary Science Institution radar imagery of Bennu. Credit: NASA/GSFC/UA.

3.3 Site Selection Campaign

The purpose of Site Selection Campaign is for the science team to study the asteroid, map it and select a sample site. This campaign has three phases Detailed Survey, Orbital B, and Reconnaissance. The phase concludes by selecting one site for sampling. This campaign provides the first detailed measurement of Bennu's position and refines the size and rotation of Bennu for the Navigation team. 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.

The spacecraft will leave orbit and perform another series of hyperbolic flybys, Detailed Survey, with a 3.5 km closest approach. These flybys will provide a high-resolution shape model and global science picture for Bennu. By the end of Detailed Survey up to twelve sites will be identified for additional study. The spacecraft will then re-enter orbit, Orbital B, at a 1 km altitude where site specific science data collection will take place. At the end of Orbital B two candidate sample sites will be selected for the next phase, Reconnaissance.

The Reconnaissance phase will have the spacecraft leave the 1 km orbit and fly over up to four candidate site at altitudes of 225 m to collect data to assess their sampleability. The candidates sites are then reduced to two and a 525 m fly over are performed to characterize their science value. One site will then be selected for sampling.

3.4 Sample Collection Campaign

The Sample Collection Campaign has two parts, Rehearsals and Sampling. Once the sampling site has been selected the team will rehearse the sample collection activities, Figure 2. The Rehearsal phase has the team performing the Checkpoint maneuver then returning to orbit. The next rehearsal takes it a step further where the Checkpoint and Matchpoint maneuvers are performed and then the spacecraft is returned to the 1 km orbit. After successfully performing these maneuvers the team is ready for 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).

3.5 Earth Return and Reentry

As OSIRIS-REx approaches Earth, the plans for reentry are reviewed 6 months before arrival, and preparations begin. The spacecraft 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 spacecraft perigee to 250 km altitude leaving the spacecraft in a 1.0 by1.9 AU solar orbit that will not re-intercept Earth.

The spacecraft 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 spacecraft 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.

4 Mission Operations Design and Trades

Going to an asteroid to retrieve samples has some aspects of pioneering. Based on the Rosetta experience of images from Rosetta mission (figure 1a) the operations need to be flexible and plan for the unexpected.

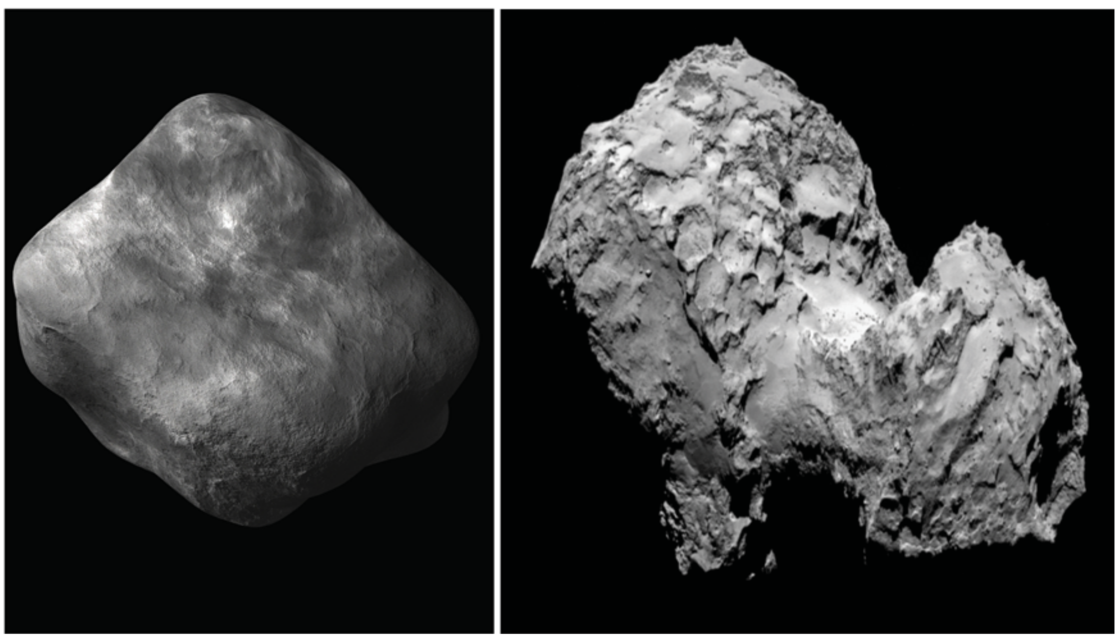

Figure 1a Pre-Encounter Comet Churyumov-Gerasimenko vs actual images (Credit ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA)

This paper emphasizes the use of operations best practices that were used in previous missions, that were tailored for a small body sample return mission. The navigation challenges dealing with small bodies with minimum gravity and landing in a small area are unique to this mission. A slow approach for asteroid operations is documented in the Design Reference Mission (DRM). The need for discipline and higher fidelity of operations analysis and opportunity of working with University students allowed the infusion of tools such as AGI's Satellite Tool Kit (STK/SOLIS) and Vitech's CORE systems engineering. The remainder of the paper will describe in further details the implementation of these best practices.

4.1 Navigation is Key to Mission Success

Navigation around the asteroid requires more accuracy than conventional radiometric tracking. 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. Flight Dynamic Systems (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.

In order to plan observations we have to know where the spacecraft will be several weeks into the future. The weak gravity of Bennu is a problem in knowing where the spacecraft is going to be. Solar Radiation Pressure (SRP) is significant compared to gravity and SRP varies depending on orientation of spacecraft and solar panels
Other forces are important too, e.g. heat radiating from the spacecraft. Uncertainties on the location of the spacecraft deteriorate with time and we need frequent updates on the spacecraft position.

The mission needs accurate navigation and deploys optical navigation. The successful transition from star based navigation to landmark navigation performed during Orbital A is the key to mission success.

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

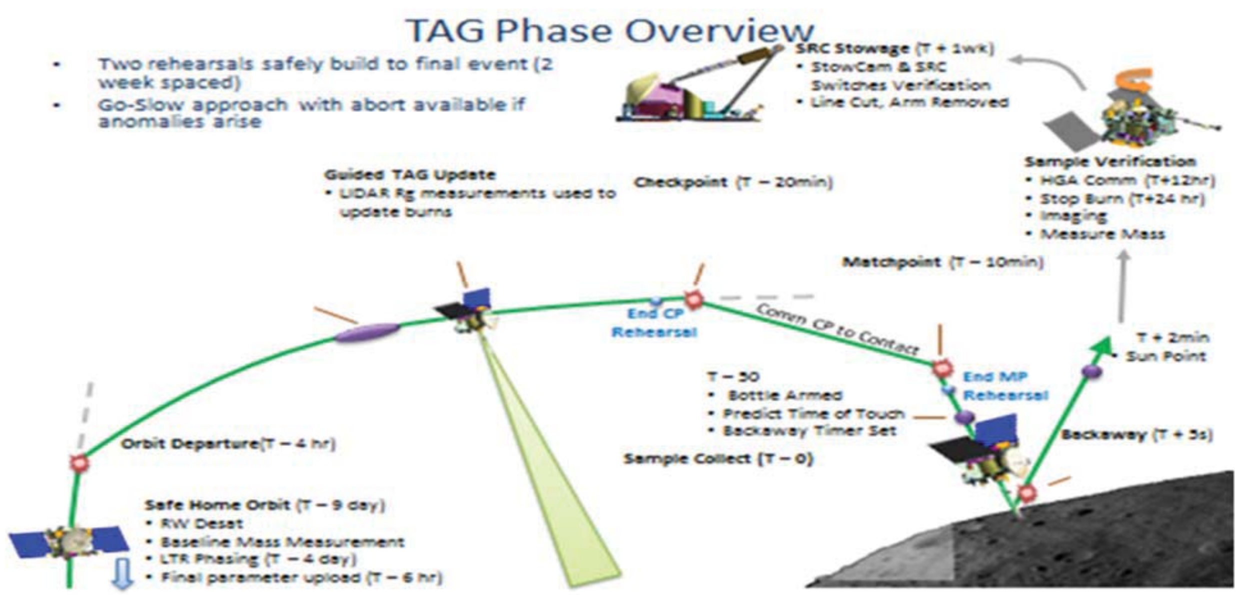

Figure 2 Touch and Go (TAG) design

Touch And Go (TAG) is unique to OSIRIS-REx and requires careful planning and design. The design focuses on navigation approaches.

There are three methods to perform Touch and Go navigation:

- Ground in the loop – all ground
- Lidar – guided TAG, where using Lidar measurements we know distance to asteroid. Lidar meets requirement of landing within 25 meter ellipse and is the current baseline.
- Natural Feature Tracking (NFT) - Autonomous on spacecraft. Using features of the asteroid we collect images and improve our guidance. NFT improves the knowledge and if proven successful will be a path for future landing missions that require landing accuracy of several meters. NFT has just been added to the design and will be analyzed further.

4.2 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.

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.

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 Bennu 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.

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 of human factors that had previously been overlooked. Example of human factor is using a human calendar; on specific days of the week perform an activity (uplink).

The spacecraft subsystem design has been stable since the proposal phase and is based on the heritage Lockheed Martin MAVEN mission.

In preparation for CDR, the spacecraft team performed an analysis, the Baseline Reference Mission (BRM), showing how a day in the life will be executed including spacecraft constraints.

Obvious constraints on observations are

- data volume
- Sun keep-out zones.

Less obvious constraints are

- Thermal - the spacecraft gets hot during 4.3-hour observations (for global data) and needs up to 24 hours to cool down before more observations can be made.
- Navigation uncertainties with most missions are small and can usually be ignored, we need to recognize that the longer we plan from the last orbit determination (OD), the greater is our uncertainty.
- Solar Radiation Pressure applies a torque to the spacecraft that is compensated by the reaction wheels. The wheels can only absorb so much angular momentum before they need to be spun down (using thrusters). Thus placement of the desats is critical since they also impact the trajectory.

4.3 Late Update

To address navigation uncertainty requires a fast turnaround of navigations update throughout the system. The requirement of the ground system is to respond within 24 hours to a navigation update and upload it to the spacecraft. This is the normal practice in the mission and needs to be maintained for almost two years. To eliminate human errors and reduce operations, software tools have been implemented. The flight software interface was updated to use Absolute Target List (ATL) approach to expedite command updates. ATL allows coordinate and timing changes without need to compile and test entire command sequences. The Science planning tool automatically generates ATL and command files. Lockheed Martin has automated many of its operational verification processes.

4.4 Planning and Analysis Tools

Key to the 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 module base system engineering tool. The ground team will be testing these interfaces in a series of Ground Readiness Tests (GRT). All verification activities and test artifacts are tracked in CORE.

The DRM is managed by Mission Systems 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 the trajectory for each DRM phase. The Spacecraft Design team developed a Baseline Reference Mission (BRM). The BRM identified thermal and High Gain Antenna (HGA constraints) that were fed back into the timeline to further ensure the DRM can be performed.

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

To support the details of command generation and minute by minute activities a planning system is being implemented. The planning tool is the OSIRIS-REx Visualization Tool (J-Asteroid by ASU) and STK/SOLIS. Figure 3 summarizes the implementation of the OSIRIS-REx analysis and planning tools strategy. Validation of OSIRIS-REx command process is done by executing detailed DRM operations scenario using the ground system. The goal is to have J-asteroid with one validated command scenario per DRM phase into J-asteroid prior to launch.

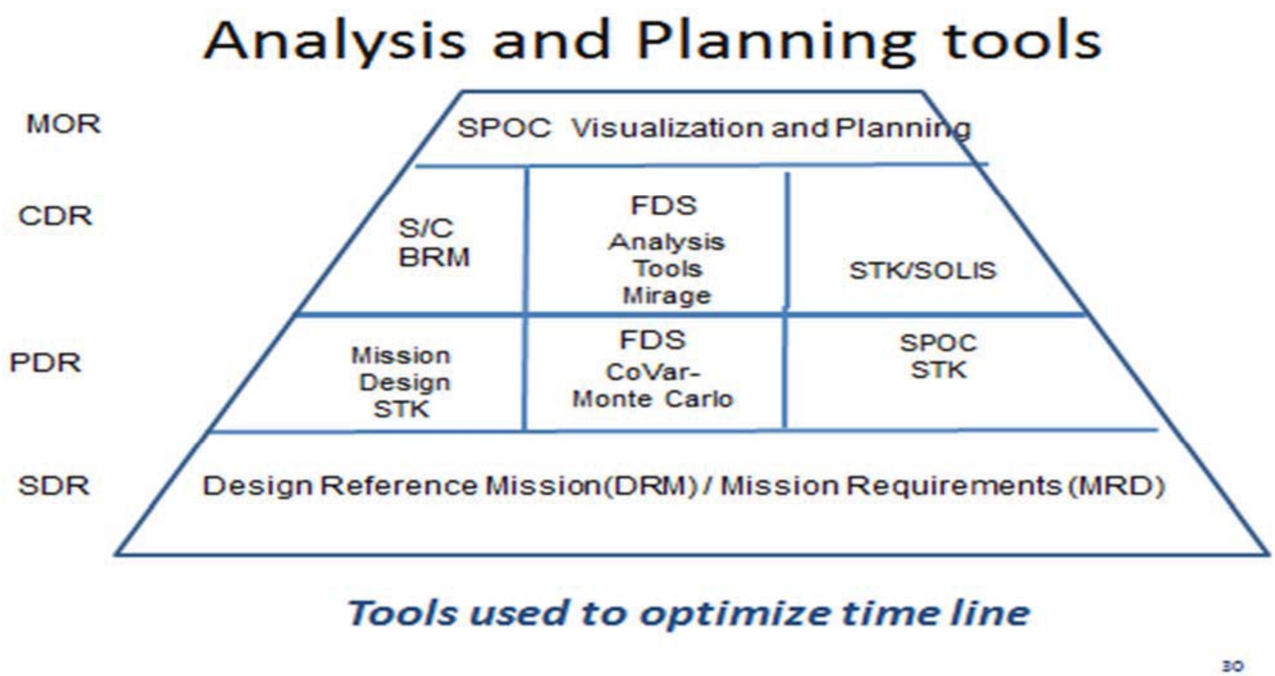

Figure 3 Requirements, Analysis and Planning Tool Implementation

4.5 Operations Best Practices

The project deploys a set of best practices related to operations. Below are some examples.

4.5.1 Continued Implementation of 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 the previous step.

Upon start of phase B the team met with a number of small bodies mission projects. Jet Propulsion Laboratory (JPL)/Dawn and Applied Physics Lab (APL) emphasized the importance of implementing a planning process early in the life cycle. We visited with European Space Agency/Rosetta twice. During the first visit, ESA/Rosetta emphasized the need for an independent navigation camera. That recommendation was incorporated into spacecraft design after PDR. Our second visit to ESA/Rosetta emphasized the use of a human "friendly" schedule to prevent personal "burn out". The project met with Japan Aerospace Exploration Agency (JAXA)/Hayabusa 2 in April 2015 and the Japanese emphasized the importance of Navigation campgain and only after that perform detailed science planning.

Another practice is shadowing other missions. OSIRIS-REx ground personnel shadowed MAVEN since CDR through its successful launch in November 2013 and Mars Orbit Insertion in September 2014.

4.5.2 Requirements Management & Testing

The OSIRIS-REx ground system uses the CORE [2] Engineering tool to capture requirements, architecture and interfaces. Realizing heritage ground system providers use the same documents over and over, and don't emphasis "systems engineering". We implemented lessons learned from MAVEN and emphasized better/smarter systems engineering using CORE. We took advantage of access to University of Arizona students.

A series of Ground Readiness tests (GRT) were developed to sell off requirements in 6 increments.

In addition to the 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 tests are conducted throughout the mission life time starting with the ATLO System Verification Tests (SVT) that demonstrates the flight-like sequences. During the operation phase (post launch) Operations Readiness Tests (ORT) will be conducted for the Bennu science phase, TAG, and SRC Release. The ORTs will be followed by a Critical Event Readiness 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).

4.5.3 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, CDR and now preparing for MOR. 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 reviewed as part of the Science 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.

4.5.4 Science Team Interface

The OSIRIS-REx science team has been heavily involved in the mission. The science team is integral to mission success as they are responsible for site selection. The science team responded similarly to other ground elements and went through design review. The integration of the science team was recognized by the review teams as strength.

4.5.5 Co-Location

To improve communications in phase E we plan to co-locate team members at the Mission Control. The process has started already in the development phase as three of the Flight Dynamics teams are located in Denver. Co-location helps improve communication.

5 Summary

Planning for OSIRIS-REx successful mission operations is a continuous effort. The unique nature of OSIRIS-REx requires special attention to mission design, navigation and Touch and GO. Analysis and planning tools used in Phase C-D will be the basis for detailed planning during phase E. This is enhanced by using operations best practices.

The preparation for operations is continued effort, and one must keep an open mind and accommodate changes.

6 Acknowledgement

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6.1

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