The OSIRIS-REx Asteroid Sample Return Mission

Edward Beshore
ebeshore@lpl.arizona.edu
(520) 621-4900

Dante Lauretta
lauretta@orex.lpl.arizona.edu
(520) 626-1138

William Boynton
wboynton@orex.lpl.arizona.edu
(520) 621-6941

Christopher Shinohara
chriss@orex.lpl.arizona.edu
(520) 621-2471

Lunar and Planetary Laboratory
University of Arizona
Tucson, AZ 85705

Brian Sutter
brian.mspc.sutter@lmco.com
(303) 971-7731

Lockheed Martin Space Systems Co.
Littleton, CO 80125

David Everett
David.F.Everett@nasa.gov
(301) 286-1596

Jonathan Gal-Edd
jonathan.s.gal-edd@nasa.gov
(301) 286-2378

Ronald Mink
ronald.g.mink@nasa.gov
(301) 286-3524

Michael Moreau
michael.c.moreau@nasa.gov
(301) 286-8382

Jason Dworkin
jason.p.dworkin@nasa.gov
(301) 286-8631

NASA Goddard Space Flight Center
Greenbelt, MD, 20771

Abstract — **In September of 2016, the OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, Security, Regolith EXplorer) spacecraft will depart for asteroid (101955) Bennu, and when it does, humanity will turn an important corner in the exploration of the Solar System. After arriving at the asteroid in the Fall of 2018, it will undertake a program of observations designed to select a site suitable for retrieving a sample that will be returned to the Earth in 2023.**

The third mission in NASA's New Frontiers program, OSIRIS-REx will obtain a minimum of 60 g of a primitive asteroid's surface, the largest sample of extra-terrestrial material returned to the Earth since the end of the Apollo lunar missions (Figure 1). OSIRIS-REx will also return a separate sample of the fine-grained surface material that is <1 mm in diameter.

TABLE OF CONTENTS

1. THE THIRD NEW FRONTIERS MISSION............1
2. MISSION OBJECTIVES.......................................2
3. TARGET SELECTION...3
4. THE OSIRIS-REX MISSION DESIGN...............3
5. SCIENCE PAYLOAD...7
6. OPERATIONS...8
7. CONCLUSION..10
8. REFERENCES..11
BIOGRAPHIES...11
DEDICATION AND ACKNOWLEDGEMENT..........13

1. THE THIRD NEW FRONTIERS MISSION

Every 10 years, the National Research Council (NRC) prepares the Planetary Science Decadal Survey. This document is used to inform NASA and other federal agencies about the most pressing questions in planetary science, and offers specific recommendations for programs to help answer those questions. In 2003, the NRC released "New Frontiers in the Solar System: An Integrated Exploration Strategy" [1], endorsing the development of the New Frontiers Program, a medium-scale, principal-investigator-led series of missions, and intended to fly twice each decade. The NRC recommendation also included mission concepts that addressed several cross-cutting themes, including the history of the early Solar System, the origin of volatile and organic materials needed to support life, and the processes that govern the evolution of planetary systems.

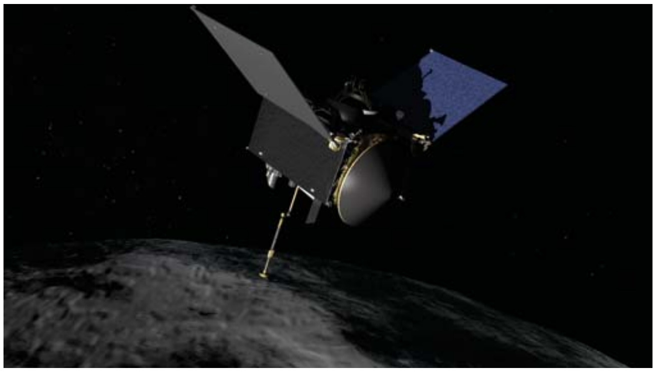


Figure 1. The OSIRIS-REx spacecraft will obtain a minimum of 60 g of a primitive asteroid's surface and return it to Earth in 2023.

In 2007, the NRC was asked to provide criteria and guiding principles to NASA for determining the list of candidate missions for the upcoming third New Frontiers selection. The resulting document "Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of

978-1-4799-5380-6/15/$31.00

Opportunity" [2], identified asteroid sample return as a high-priority mission concept. A variety of developments since the Decadal Survey, when combined with the strong initial rationale in the 2003 document, prompted the committee to elevate the priority of this mission concept.

In May of 2011, NASA selected OSIRIS-REx as the third New Frontiers mission, with a Principal Investigator (PI)-managed cost-cap of ~$850M plus launch vehicle. (Previous New Frontiers selections were *New Horizons*, which will encounter Pluto in July of 2015; and *Juno*, which will explore the Jovian environment one year later, in 2016.) Under the leadership of PI Dante Lauretta of the University of Arizona, and in partnership with Lockheed Martin Space Systems (space craft and mission operations) and the NASA Goddard Spaceflight Center (project management), OSIRIS-REx will depart for its target aboard an Atlas V 411 evolved expendable launch vehicle during a 39-day launch window that opens on September 3, 2016.

2. MISSION OBJECTIVES

The Decadal Survey recommendation came about because asteroids represent a rich source of scientific information about conditions in the early Solar System, but there are other motivations for our mission. Some asteroids are a potential threat to the Earth's inhabitants, and improving our ability to predict the long-term ephemerides of objects whose orbits cross the path of the Earth can provide the warning needed to mitigate an impact. In addition, small Solar System bodies may harbor resources for terrestrial use or to aid future planetary exploration. A better understanding of asteroid compositions will help us determine if we can rely on them as a source of useful materials. OSIRIS-REx also provides the first ground truth for telescopic observations of carbonaceous asteroids.

OSIRIS-REx will help us answer these questions, all of which are addressed by five mission science objectives.

1. *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.*

   Our target asteroid, (101955) Bennu[1], has been the subject of considerable scrutiny from Earth, and OSIRIS-REx affords an exceptional opportunity to compare our Earth-based observations with close-up measurements. This comparison may help us better interpret the observations of other asteroids made over the last 65 years.

2. *Map the global properties, chemistry, and mineralogy of a carbonaceous, primitive asteroid to characterize its geologic and dynamic history and provide context for the returned samples.*

   The first goal of any explorer upon arriving at a new location is a global survey and mapping campaign to put subsequent observations in their proper context. Such a survey may also help us better understand how Bennu found its way into the inner Solar System, and provide important clues to its early history.

3. *Document the texture, morphology, geochemistry, and spectral properties of the regolith at the sampling site in situ at scales down to the sub-cm.*

   To select a sample site, global mapping campaigns will be followed by detailed observations of candidate sites to determine if a sampling attempt will be safe, that material for sampling will be found, and that the site represents an area of high scientific interest. Careful observations at this scale will allow us to better understand the context of the returned sample.

4. *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.*

   One of the most important questions in planetary science today relates to the source of organic materials and water, which may have influenced the origin or early evolution of life on Earth. Were these materials present at the creation of the Solar System, or were they delivered to the Earth after its formation? The carbonaceous asteroids, suspected to be chemically unaltered since the formation of the Solar System, may hold the answers to these questions. Definitive answers may only come by direct examination of samples using a variety of methods. Sample return will also allow study using future laboratory techniques not available to us today.

5. *Measure the Yarkovsky effect on a potentially hazardous asteroid and constrain the asteroid properties that contribute to this effect.*

   Asteroids absorb sunlight and re-radiate it in the thermal infrared. For asteroids rotating in a single axis, this results in a small, but continuous force applied in a preferential direction. Called the *Yarkovsky effect*, this force can drive bodies into resonances between the Sun and Jupiter or Saturn, resulting in the perturbation of the asteroid's orbit. This has been identified as a causative factor in the creation of Earth-crossing objects and this force also limits our ability to predict

---

[1] The OSIRIS-REx communications and public engagement program, in partnership with the Planetary Society, invited school children around the world to suggest a more memorable name for our asteroid. The winning entry from a North Carolina 3rd grade student was Bennu, the Egyptian name of a grey heron. The discoverers of the object, the Lincoln Near Earth Asteroid Research (LINEAR) Survey kindly agreed to submit the renaming proposal to the International Astronomical Union committee on Small-Body Nomenclature, who made the new designation.

the position of these objects much beyond 100 years. Understanding the characteristics of asteroids that mediate the magnitude of the Yarkovksky effect will help improve our ability to precisely determine the orbits of potentially hazardous objects further into the future.

3. TARGET SELECTION

Selecting a suitable target for the OSIRIS-REx mission began with the 500,000 or so asteroids known at the time of our proposal. Considerations for the delta-V of available launch vehicles suggested that Near-Earth asteroids (NEAs), whose orbits bring them close to the Earth, were a logical place to begin the search. At the time, over 8000 NEAs were known. Further analysis revealed that of these, only 350 had orbits that were optimal for a sample return mission within the calendar constraints of the New Frontiers solicitation, mass constraints, spacecraft design, and available launch vehicle delta-V. Of the 350 objects with optimal orbits, only 29 had diameters greater than 200 m. Objects smaller than 200 m often have fast rotation rates (< 2 hours) or exhibit non-principal axis rotation (tumbling) that could complicate proximity operations. It was also feared that smaller, rapidly rotating objects would throw off the loose material needed for sampling. Of the final 29 candidate objects, only five had carbonaceous spectral features. These were likely primitive asteroids that have seen minimal physical alteration since the Solar System formed 4.5 billion years ago. It was these objects that were likely to yield the answers that we seek about the earliest stages of planetary formation. One of them was Bennu.

With this narrowed field, OSIRIS-REx scientists began a comprehensive campaign of observations using ground- and space-based telescopes. Two good observing opportunities for Bennu occurred during its discovery epoch in 1999-2000 and then again in 2005-2006. Both afforded opportunities for observations by the planetary RADAR system at Arecibo, Puerto Rico. These observations produced a shape model with approximately 7 m resolution (Figure 2), bulk density measurements, and precise orbital characteristics [3,4].

In addition, during these and the 2012-13 apparition, numerous ground-based and Hubble Space Telescope observations yielded spectroscopy and photometric data, confirming the carbonaceous nature of the object, and refinements of its rotation rate [5]. Other observations included thermal infrared measurements from the Spitzer Space Telescope [6], which are important for assessing environmental conditions for the flight system, and provide clues about regolith characteristics.

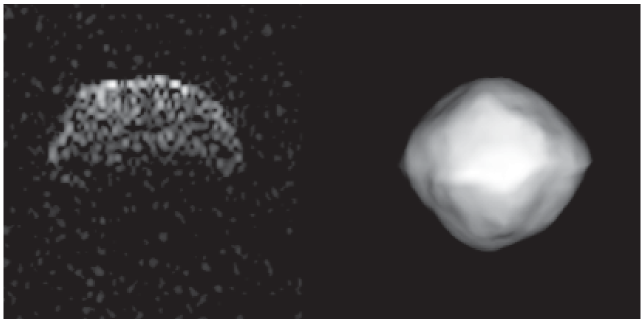


Figure 2. A comprehensive campaign of observations using ground- and space-based telescopes, including RADAR (left), yielded a shape mode of asteroid Bennu with approximately 7 m resolution (right).

The preponderance of high quality observations and the confirmation of the (relatively) benign nature of Bennu resulted in its selection as the mission target prior to submission of our proposal to NASA for a New Frontiers Mission. The results of the observational campaigns on Bennu were collected internally in a document known as the *Design Reference Asteroid*, or DRA. This configuration-controlled DRA formed an important resource for mission planners and spacecraft designers, as it summarized all that was known about the object and its environment. A recent version of this document has been made publically available [7]. Since that time, numerous peer-reviewed publications based on these observations have appeared. Table 1 summarizes some of the information obtained during our ground-based studies of Bennu.

4. THE OSIRIS-REX MISSION DESIGN

Science goals for the OSIRIS-REx mission are met through a number of science products made from observations taken over several mission phases. These phases have been carefully documented in a *Design Reference Mission* (DRM) document, which along with the DRA, formed a comprehensive resource around which the flight system and payload engineers could begin their design and analysis work.

The DRM is also a validation mechanism to ensure that our mission addresses the science and engineering objectives of the mission, and forms the foundation for developing detailed case studies that service observation planning and commanding efforts by our operations teams.

Launch and Outbound Cruise

The 39-day OSIRIS-REx launch window opens on September 3, 2016. With a wet mass of 2110 kg, OSIRIS-REx will leave Earth on a direct outbound trajectory with a delta-V of 1400 m/s. Hyperbolic injection C3 is fixed at $29.3 km^2/s^2$ The outbound cruise includes a Earth gravity assist maneuver just over 1 year later to match the inclination of the orbit of the spacecraft with Bennu's 6 degree inclination with respect to Earth.

Table 1. Some physical characteristics of asteroid Bennu.

Mean Diameter	492 ± 20 m
Bulk Density	1260 ± 70 kg m^{-3}
Mass	$7.8 \times 10^{10} \pm 0.9 \times 10^{10}$ kg
GM	5.2 ± 0.6 m^3 sec^{-2}
Semi-major Axis	$1.126391025996 \pm 4.2 \times 10^{-11}$ au
Perihelion	0:896894360 ± 2.4 x 10^{-8} au
Orbital Period	436.648727924 ± 2.4 10^{-8} days
Minimum Orbital Intercept Distance	0.0003223 AU
Semi-Major Axis Drift Rate	$-19.0 \times 10^{-4} \pm 0.1 \times 10^{-4}$ au Myr^{-1}
Rotation Period	4.29746 ± 0.002 h
Obliquity	175 ± 4 deg
Non-principal axis rotation	No evidence
Absolute Magnitude incl. Opposition Effect	20.4 ± 0.05
Geometric Albedo at 0.54 μm	0.045 ± 0.015
Thermal Inertia	310 ± 70 m^{-1} $s^{-0.5}$ K^{-1}

Global Observations

Our science mission begins with a period of global observations to provide an overall assessment of the asteroid topography and shape, mass, mineralogy, temperature, and gravity field. This will permit early assessments of the deliverability, safety, sampleability, and scientific interest of various regions on the surface, and allow mission management to make an initial selection of up to 12 sites for closer scrutiny.

Our first observations occur about 10^6 km from Bennu during a 68-day approach that begins on September 12, 2018 with surveys for dust plumes and natural satellites. Discovery of either of these would trigger a full safety assessment and a review of the approach strategy. Additional observations will allow us to obtain required "disk integrated" photometric and spectral data to compare with Earth-based measurements of Bennu and other asteroids. During the final phases of approach, imaging will give us our first detailed look at Bennu, and allow the creation of a shape model needed by both navigators and science planners using the technique of sterophotoclinometry [8]. At the completion of approach, our first mission science objective will be met — characterizing the integrated global properties of Bennu.

Approach will be followed by preliminary survey (Figure 3), which consists of three hyperbolic passes over the North and South poles and equator at 7 km from the center of the asteroid (Hereafter, all spacecraft/asteroid range measurements will be referenced to the center of the asteroid unless otherwise indicated.) These passes will permit radio observations to determine Bennu's mass, a prerequisite to planning the maneuvers to place our spacecraft into orbit. We will also obtain data from our lidar science instrument for the first time, along with additional imagery. A preliminary asteroid coordinate system will also be developed using data from this phase.

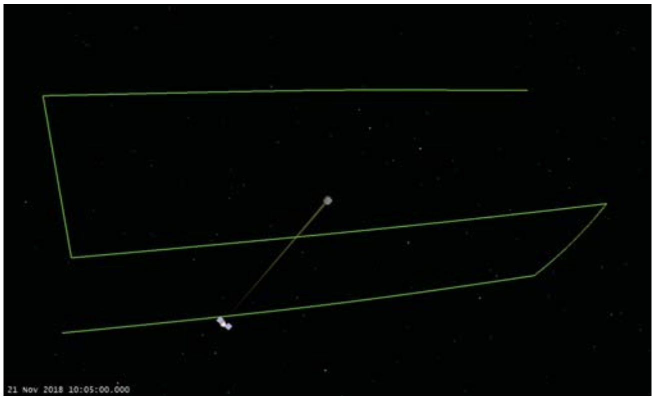


Figure 3. Preliminary survey consists of three hyperbolic passes (green) over the North and South poles and equator at a range of 7 km.

After preliminary survey, the OSIRIS-REx spacecraft will be placed into a 1.5 km orbit (Orbital A) for one month. During Orbital A, our navigation teams will fully transition from star-based to landmark optical navigation, and will establish the routines of orbit determination and maneuver planning that will characterize their activities for nearly a year. As time and circumstances allow, additional high-resolution science imaging may take place during Orbital A to improve topographic maps and finalize our understanding of the rotation state of the asteroid.

Our global investigation will conclude with Detailed Survey, an ambitious phase requiring multiple hyperbolic passes of Bennu. The first of these passes will be at 3.5 km and transit over four sub-spacecraft points at 40° North and South latitude and at 10 AM and 2 PM local time on the surface. Images and lidar spots from each of these points taken through a full 4.3 hour asteroid rotation will provide high resolution, stereo imagery of the entire surface. This global imagery will be used for the creation of topographic map products accurate to ~0.5 m and reveal surface features around ~21 cm in size.

A second set of seven 5-km passes will fly through points above the equator, spaced over multiple local times of day on the surface (Figure 4). Such spacing ensures a number of independent illumination angles and observing geometries that reveal important details about surface properties. These observations will provide spectroscopic and spectrophotometric measurements that will reveal reflectivity, mineralogical distributions, surface temperatures, and surface thermal characteristics to help round out our global assessment of the asteroid. At the end of detailed survey, our PI will have the final information to make an initial selection of up to 12 candidate sites. In addition, the work to accomplish the second mission science objective should be complete – mapping the global properties of the asteroid.

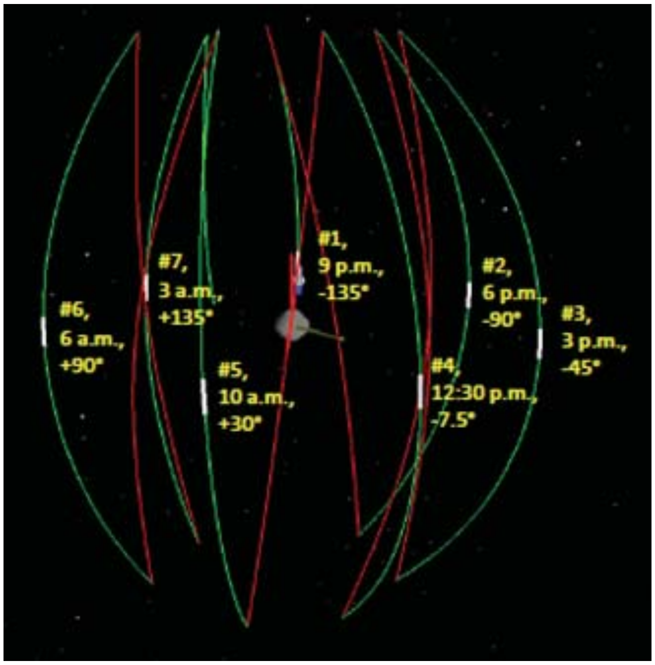


Figure 4. Detailed Survey concludes with seven 5-km passes through points above the equator, spaced over multiple local times of day on the surface.

Site-Specific Survey

The next task of the mission will be reconnaissance of the initial selection of sites in order to assess the suitability of each for a sampling attempt. Site-specific observations will commence after insertion into a 1-km orbit (Orbit B.) A 9-day period of gravity field mapping using radiometric observations will provide valuable insights into internal structure of the asteroid.

Site-specific Orbital B observations will include imagery from multiple illumination angles that resolves objects as small as 5 cm, detailed lidar observations, X-Ray spectroscopy, and thermal emission measurements to confirm predictions for maximum temperatures at the site. When site-specific observations are not being made, the spacecraft will be nadir pointed to support high resolution survey-style observations using imagery, spectroscopy, and lidar.

The Orbit B phase will conclude with a downselect to two primary and two secondary sites. The primary sites will be the target of one final set of reconnaissance observations. These observations will consist of high resolution imaging taken from 225 m above the surface and will resolve objects as small as 2 cm. Observations with other instruments will be obtained during higher reconnaissance passes at 525 m from the surface. Secondary sites will serve as alternates in the event that both primary sites fail to meet safety or sampleability requirements.

At the conclusion of reconnaissance, the site-selection team will make its recommendations to the PI for a final decision. Reconnaissance completes much of the science investigation needed to meet the third mission science requirement — centimeter-scale observations of the sample site. It also lays the groundwork for completing the fourth — sample return.

Touch-and-Go Sampling

The OSIRIS-REx mission has adopted a sampling strategy referred to as Touch-And-Go, or TAG. TAG uses the momentum of a slow downward trajectory of the spacecraft to maintain contact with the surface just long enough to obtain a sample, followed by a controlled back-away burn. One of the most obvious benefits of TAG is avoiding the need to develop a system for landing on the surface and collecting a sample. The low-G environments of small objects make extended contact problematic, requiring a system to secure the spacecraft to the surface to ensure that sampling doesn't launch the spacecraft away from the surface in an uncontrolled manner. TAG does, however, require an observing campaign, like the one described, to find a site with suitable sampleability characteristics – loose, relatively fine-grained material that supports a quick sampling attempt.

OSIRIS-REx will use a novel method to collect the sample. The spacecraft's Touch-And-Go-Sample-Acquisition-Mechanism, or TAGSAM, is a simple annulus with a filter screen on the outside circumference, held at the end of an articulated arm that can be extended several meters from the spacecraft (Figure 5).

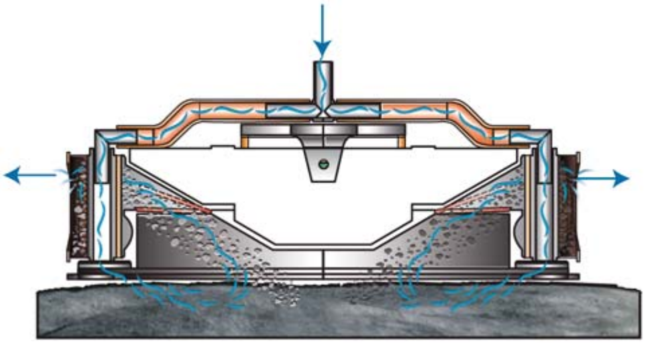


Figure 5. TAGSAM is a simple annulus with a filter on the outside circumference. Nitrogen injected into the interior of the annulus entrains material, forcing it through the filter, where it is captured.

The head is mounted on a wrist assembly that allows it to articulate and make full contact even if the angle of approach is not completely normal to the surface. During contact, which can last for up to 5 seconds, high-purity N_2 gas will be injected into the interior of the annulus where fines and small pebbles up to 2 cm in size will be entrained in the gas flow. The only exit for the gas and surface material will be through the filter on the outside, where the material is captured.

The sample will be collected and kept pristine though an extensive contamination control plan. The plan limits the total contamination burden on the sample via proxies to species of scientific interest by limiting sensitive surfaces to IEST-STD-CC1246D 100A/2, 180 ng/cm^2 total amino acids and hydrazine. Furthermore, the analysts are armed with an extensive catalog of witness plates collected during spacecraft construction and test as well as during different phases of the mission.

Mission science requirements call for a minimum of 60 g of material to be retrieved using TAGSAM. A number of tests during microgravity flights using surface simulants have demonstrated collections of over 600 g (Figure 6). To help ensure that some sample is obtained even if the primary collection technique fails, and to trap a surface-weathered sample, the TAGSAM head has a number of stainless-steel Velcro pads that can capture fines during its brief contact with the surface. The TAGSAM subsystem has enough N_2 to make three sampling attempts.

Figure 6. During microgravity flights, experiments with the TAGSAM head have collected sample amounts in excess of 600 grams.

Requirements demand that we deliver the TAGSAM head to within 25 m of a selected point on the surface with greater than 98% probability. Plans for descent to the surface begins with a burn from a 1 km orbit, followed by a "checkpoint" burn at a predetermined point 125 m from the surface. Finally, a "matchpoint" burn at 55 m will match the asteroid rotation rate and set our descent rate to the surface. Orbit knowledge uncertainty and orbit departure maneuver execution error precludes an uncorrected trajectory to the sample site. Instead we will use an autonomous technique called "Guided TAG" which, after departing orbit, will use the navigation lidar to detect the time of a range threshold crossing, followed by a range measurement at a specific time to make corrections to the checkpoint and matchpoint burns (Figure 7).

Because TAG is a critical event, we will adopt a "go slow" approach that will include at least two rehearsals. One will exercise the period from departure to checkpoint before returning to orbit; the next will take us from orbit to matchpoint before a return to orbit. Each time we will collect and analyze tracking data, lidar, and imagery to help us understand the performance of the system before proceeding to the next step. Only when we are satisfied that our chances of success are acceptable will we proceed with TAG. We anticipate the first TAG attempt will take place in October of 2019 when spacecraft-Earth distance will be ~1.8 AU. The entire event will be imaged by onboard cameras at a rate of just under one frame per second.

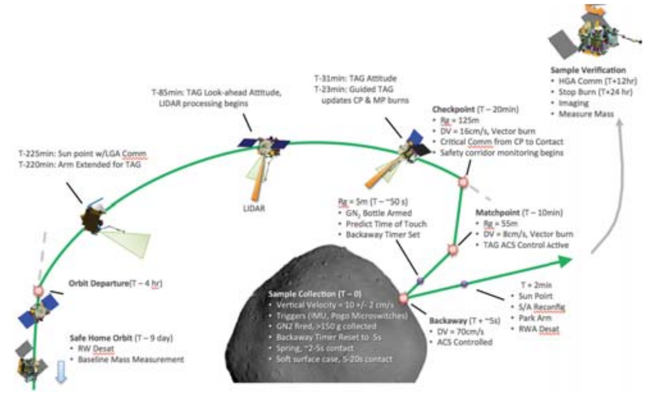


Figure 7. OSIRIS-REx we will use a technique called "Guided TAG" to navigate to the surface of the asteroid. After departing from a 1 km orbit, the navigation lidar detects the time of a range threshold crossing, followed by a range measurement at a specific time to correct burns made during the descent.

After TAG is complete, we will measure the mass of the sample by comparing the change in angular momentum of the spacecraft with the TAGSAM arm extended after the sampling attempt to a similar measurement made before TAG. A sample mass measurement of more than 60 g will result in a decision to stow the TAGSAM head in the Sample Return Capsule (SRC) similar to the one used on the successful Stardust mission [9]. The TAGSAM arm will position the head in the open SRC to allow its capture by three cams, and then an explosive bolt will fire to sever the connection between the TAGSAM head and arm. TAGSAM head stowage will be recorded by a special camera to confirm proper placement in the SRC. After successful stowage, the spacecraft will be put in a slow drift away from Bennu and placed in a quiescent configuration until departure in March of 2021. (Options exist to add more flexibility and margin to our mission with both early return to Earth and later departure from Bennu. The full range of these depends on the final wet mass of the spacecraft as well as the launch vehicle performance.)

Return Cruise, Earth Return, Sample Curation

Nominal departure for Earth will commence with a burn in March of 2021. After a 2-year cruise, Earth atmospheric entry of the SRC will occur in September 2023. Four hours before entry, the SRC will be released from the spacecraft bus, and a divert maneuver will be executed to place the spacecraft into a heliocentric orbit. The SRC will enter Earth's atmosphere at more than 12 km/s, slowed first by a drogue and then a main parachute, and will soft land at the US Air Force's Utah Test and Training Range west of Salt Lake City, UT. After recovery teams ensure that the SRC is safe to handle, it will be airlifted to a custom-built curation facility at the NASA Johnson Spaceflight Center. Curators will have 6 months to complete an inventory of the returned sample, after which time, investigators from around the world may apply for material and witnesses using an established astromaterials loan request. A sample will also be sent to the Canadian Space Agency in exchange for their contribution of the lidar. One will also be sent to the Smithsonian Institution for archive and display.

5. SCIENCE PAYLOAD

Key to achieving the mission science requirements is a set of scientific products derived from observations made by a specially-designed suite of science instruments. These include an imaging camera suite, an optical and near infra-red spectrometer, a thermal emission spectrometer, an imaging lidar system, and an X-Ray emission spectrometer designed and built by students (Figure 8).

Figure 8. OSIRIS-REx instruments (clockwise from top): OCAMS camera imaging system, OTES thermal emission spectrometer, OVIRS optical and near IR spectrometer, OLA imaging lidar, and the REXIS X-Ray emission spectrometer. Gravity field Doppler observations are obtained with the Deep Space Network (not pictured.)

The OCAMS Camera Suite

The OSIRIS-REx camera system, or OCAMS, consists of three cameras and a shared, redundant camera control module. Built by the University of Arizona, all OCAMS cameras employ 1K x 1K detectors and identical, passively-cooled focal plane electronics.

MapCam is the OSIRIS-REx mid-field imager, with a 125 mm focal length f/3.3 optical system that provides a ~70 mrad (4 deg) field of view. MapCam will search for natural satellites and plumes during approach and will provide imagery needed for base maps, global shape model development, and spin-state measurements. MapCam is equipped with a filter wheel that contains four filters from the Eight-Color Asteroid Survey (ECAS) filter system, which is the standard for ground-base spectrophotometry of asteroids. MapCam filters will also enable the production of color images, and with its ability to produce color indexes associated with some important spectral features, can act as a partial backup for the loss of the visible-light spectrometer.

PolyCam is a narrow-field, 630 mm focal length f/3.15 Ritchey-Chretien telescope that will provide the imaging used for producing boulder maps, and for close scrutiny of the sample sites during the Orbital B and Reconnaissance phases of the mission. During reconnaissance, the changing distance of the spacecraft from Bennu during imaging requires that PolyCam have a variable focus. This is implemented by moving an optical element directly in front of the detector.

SamCam is a wide-angle camera that provides context imaging during our recon passes and records the sampling event. It has a 28 mm focal length f/5.5 system, and like MapCam, is equipped with a filter wheel. The filter wheel contains three clear filters that protect the objective from dust and damage during sampling, and can be changed in the event a second or third attempt is required. In addition, a simple optical element in the fourth filter wheel position can change focus for inspection of the sampler head before stowage.

The OVIRS Visible/IR Spectrometer

The OSIRIS-REx Visible/IR Spectrometer (OVIRS) is a point spectrometer that provides coverage in the range of 0.4 to 4.3 μm. This wavelength range covers spectral bands needed to identify key mineral species, water, and organic materials. When it executes its global survey observations during detailed survey, surface resolutions for an OVIRS spot will be 20 m. OVIRS is passively cooled and uses a novel linear variable filter design to cover its wavelength range. At 1 μm, resolving power ($\Delta\lambda/\lambda$) will be about 200. OVIRS is built by team members at NASA's Goddard Spaceflight Center.

The OTES Thermal Emission Spectrometer

Bennu is a dark object, with an albedo of ~4 percent. At closest approach to the Sun, regions on its surface may reach 350° K. To ensure spacecraft safety we must confirm the temperature of Bennu upon arrival. Accurate temperature measurements taken over several times of day will provide us with the information needed to create thermal models that include estimates of thermal inertia — the rate that thermal energy moves through Bennu's surface, and an important clue for finding the loose regolith needed for sampling. Thermal emission measurements, coupled with radio science observations, will also provide needed data to characterize the Yarkovsky effect, our fifth mission science objective.

Measurements from the OSIRIS-REx Thermal Emission Spectrometer, OTES, will provide us with this information. Built by Arizona State University, OTES is a compact, spot Fourier Transform Infrared Spectrometer, and is based on similar designs used for instruments flown on the Mars Exploration Rovers and Mars Global Surveyor. OTES will measure the absolute flux of thermally emitted radiation from 5 to 50 μm with an accuracy of better than 3 percent. From a detailed survey distance of 5 km, the OTES 8 milliradian field of view will translate to a spot size of 40 m on the surface.

The OLA Scanning Lidar

Lidars have the advantage of providing a direct measurement of spacecraft range to the surface. They are useful tools in navigation, and provide straightforward observations of Bennu's bulk properties and surface topography. The OSIRIS-REx Laser Altimeter (OLA) is a scanning lidar system provided by the Canadian Space Agency and built by MDA of Canada. With two laser transmitters, OLA can range from as far away as 7 km from Bennu and as close as 500 m. OLA Observations during most mission phases will provide dense, global coverage of the surface and 5 cm resolution of proposed sample sites. In addition, OLA will provide an important, independent confirmation of topography derived from imagery.

The REXIS X-Ray Imaging Spectrometer

Solar X-rays and the solar wind constantly bombard Bennu's surface. Atoms in the regolith absorb these X-rays, causing them to become unstable and re-emit, or fluoresce, at a frequency unique to the atom. The Regolith X-ray Imaging Spectrometer (REXIS) is a small telescope that images this X-ray fluorescence, permitting maps to be made of the elemental abundances in Bennu's surface. REXIS employs coded aperture imaging, which is similar to the operation of a pinhole camera. When light shines on a pinhole, the direction of the incident light can be determined by the position of the pinhole's light. Coded aperture imaging uses many holes arranged in a pattern on a mask, allowing the direction of the re-emitted X-rays to be determined and mapped to a position on the asteroid surface.

REXIS was selected as a student experiment through a competitive selection process. REXIS will be designed and built through a collaborative effort between students and faculty at MIT and Harvard University.

Radio Science Observations

Like many missions, we will use the radio transmitter onboard OSIRIS-REx to make sensitive measurements using Deep Space Network (DSN) Doppler, and Delta-DOR (delta - Differential One-way Ranging) techniques. Radio science observations will provide detailed gravity field measurements, mass estimates, asteroid ephemerides for estimating non-gravitational forces on Bennu, and other important physical characteristics of the asteroid. Particularly interesting to our site selection teams will be maps showing the angular deviation from the local downward normal of the total acceleration vector due to gravity and rotation. These "slope" maps could inform sampleability assessments by showing where regolith accumulates.

6. OPERATIONS

The OSIRIS-REx mission has been designed with several distinct operational phases that include hyperbolic passes at 7, 5, and 3.5 km, two orbital phases, and reconnaissance over-flights at 225 and 525 m. All operations are designed to support a cautious approach to accumulating expertise and confidence around a body with a low mass, and where non-gravitational forces and low delta-v maneuvers play a significant challenge to navigation and maneuver design. Our approach to sample site selection also has driven mission design, in that it services our need to obtain an incremental understanding of the asteroid on a global level, and then again at the scale of a sample site and the sampling mechanism. These assessments require observations made from a number of geometries relative to Bennu. Such a sophisticated observing plan, along with navigational challenges, drives the design of our ground operations — navigation, planning and commanding, downlink, data verification, and science product production.

Site Selection

Our plans to produce data products from observations are a consequence of some basic mission requirements:

- We must be able to deliver our spacecraft to within 25 m of a selected location with >98% probability of success.
- When the TAGSAM head contacts the surface, our spacecraft must have a 99% probability of avoiding any damage that would prevent a successful return to Earth.

- A sample site must also have characteristics that provide TAGSAM with an 80% probability of obtaining the required 60 g of regolith.

- Finally, should two or more sites meet these criteria, our team should be prepared to say which site offers the most value to science.

Sample site selection decisions will be supported by global and site-specific maps that quantify deliverability, safety, sampleability, and science value. Each of these maps has been defined by the appropriate mission element (navigation for deliverability, project and flight systems engineering for safety, and TAGSAM and science for sampleability and science value) and will be constructed using data products derived from observations.

Product Development

From approach through TAG, members of the science team will be working out of the OSIRIS-REx science operations center, housed at the Michael J. Drake building near the University of Arizona campus in Tucson. There we will review incoming data, produce science products needed for mission operations, and together, will work to interpret the exciting new views of Bennu provided by our spacecraft.

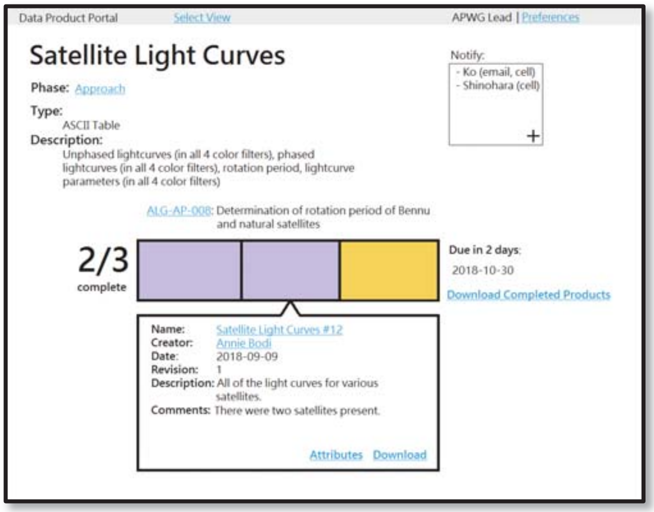
Joining the science team will be the personnel of the Science Processing Operations Center, or SPOC. The SPOC is responsible for hosting the software used to develop the science data products. The SPOC will also provide the communications and IT infrastructure, tools, and frameworks to support the science processing, planning, instrument commanding, instrument downlink and calibration pipelines, and repository for the science data. The SPOC will also ensure that science data is delivered to the NASA Planetary Data System, the public archive for all planetary missions. During formulation and development, SPOC is organizing the delivery of software from the science team and provides the verification and validation of the products that the software will produce.

Completed instrument command sequences will be uploaded from the SPOC to Lockheed Martin's Mission Systems Area (MSA) in Littleton, CO. There, the sequences will be checked for syntax and given final scrutiny to ensure that they do not violate flight rules. If necessary, they will be run through ground-based simulations before being routed to the DSN for radiation to the spacecraft. Downlinked telemetry and observations will likewise be routed to the MSA, and observations placed in a repository where they can be fetched by SPOC personnel for ingest, calibration, and delivery to the science team.

The OSIRIS-REx science team will develop products using the software that they delivered to the SPOC prior to launch. Many of these products are needed to develop the site-selection maps or navigational aids, and as such, places the science team in a time-sensitive operational role. We have carefully traced requirements to define which products are needed for site selection and navigation. Using a simple project management tool, we have prepared a resource-loaded schedule that shows us the observational dependencies of each product, the time to develop them, and the people who will prepare them. This has allowed us to accurately identify when maps will be available and to estimate when site selection decisions can be made.

Science team members responsible for the production of map and navigation products will be familiarized and practiced in their role, and will participate in post-launch science operations tests to verify execution timing and interfaces with other products. In addition, critical phases of the mission will be the subject of comprehensive operational readiness tests, some of which will include members of the science team.

During operations, science team and SPOC members will have access to a number of software products to help them with their work. Current flight system and science product status will be available through an internal science operations website. As individual observations arrive and are verified, they will be logged against a graphical data product planner (Figure 9). After all relevant observations have been calibrated, the science team and SPOC personnel responsible for products made from these observations will be notified by the planner software. If important observations are lost, the planner will be able to immediately identify the affected products and allow mission management to implement contingency operations.



Satellite Light Curves

Phase: Approach

Type:
ASCII Table

Description:
Unphased lightcurves (in all 4 color filters), phased lightcurves (in all 4 color filters), rotation period, lightcurve parameters (in all 4 color filters)

Notify:
- Ko (email, cell)
- Shinohara (cell)

ALG-AP-008: Determination of rotation period of Bennu and natural satellites

2/3 complete

Due in 2 days:
2018-10-30

Name: Satellite Light Curves #12
Creator: Annie Bodi
Date: 2018-09-09
Revision: 1
Description: All of the light curves for various satellites.
Comments: There were two satellites present.

Figure 9. As individual observations arrive and are verified, they will be logged against a graphical data product planner.

All critical science operations, including work assignments, schedules, dependent observations, and downstream users of products will be described in an on-line science operations plan implemented with our wiki software. This plan will include "playbooks" that describe off-nominal contingency operations, key decision points, and descriptions of critical science team processes and their interface with other mission elements.

When a science team product lead sits down to produce products from observations, they will be able to click on a single hyperlink that will allow them to download the calibrated data and relevant metadata from the SPOC repository into a directory on their workstation. The science team member may discard this information at any time and download the data again. When a science product is satisfactorily completed, then a data product completion meeting will be held to review the results and to discuss any deviations from the nominal processing plan. If the product meets the approval of the team leadership, the resultant data products are placed in an electronic dropbox, where the products can be compatibility checked and placed under configuration control in the SPOC repository. Once moved to the repository, the data product planner will notify schedule users of the availability of this new product.

When a product is completed, science team product leads will produce electronic briefing sheets that can be linked to the data product planner, allowing easy access by teams dependent on those products. The briefing sheets document the process and any problems encountered with a product's development. The entire hierarchy of briefing sheets leading up to the final maps will allow mission planners to review the complete provenance of any product back to its original calibrated data.

Navigation

During the course of the mission, our navigation team will be preparing orbit determinations based on radio, star- and landmark-based optical navigation techniques. These will service predicted and reconstructed ephemeris information for observation planning and calibration, and the maneuver designs to implement the mission phases. At the end of approach, the science team will deliver a million-vector shape model of the asteroid, along with a core set of surface landmarks. The navigation team will use these data during the Orbital A phase of the mission to support their transition from star-based to landmark-based optical navigation. After this time, the navigation team will enhance their set of landmarks with additional optical navigation observations taken by a dedicated camera as well as science imagery. The science and navigation teams will frequently exchange assessments of spin-state, surface landmarks, shape model, and topographic information to ensure both teams are working with consistent, high-fidelity information.

Operating in the vicinity of Bennu, our spacecraft will experience non-gravitational forces from solar radiation pressure and pressure exerted by re-emitted infra-red radiation from the spacecraft and the asteroid. These forces will be comparable to the force from the asteroid's gravity, and can create challenges in developing accurate long-term ephemerides. Frequent orbit determinations and ephemeris updates can reduce these uncertainties, but these changes put a greater burden on the navigation teams and requires a sophisticated late update process to revise planned observations to account for the latest, high-fidelity predicted ephemerides.

Another consequence of working in the small gravity field of the asteroid is the small delta-V's needed for maneuvers. Indeed, during TAG, delta-V's range between 1 and 20 cm/sec. The small sizes of these burns drive the proportional errors to be larger than typical maneuver execution errors.

To deal with these challenges, our operations teams will take a multi-pronged approach, including careful analysis, calibration, and spacecraft management to understand small force errors; formulating operations plans and cadence to deliver ephemerides to science planning, MSA, and to the spacecraft in a more timely way; revising science planning approaches and tools to optimize observations during the times when ephemerides are accurate; and taking additional time to complete required observations. If necessary, we may be able to reduce (from twelve) the number of initial sites for consideration. This would afford more time for other mission phases, and reduce some of the most challenging observations needed for the final site selection decision.

7. CONCLUSION

As the third mission in NASA's medium-scale New Frontiers program, the OSIRIS-REx mission will launch in September of 2016. When it arrives at asteroid Bennu in 2018, it will begin a detailed survey of the surface as part of the search for a suitable location to execute a Touch-and-Go maneuver to obtain 60 g or more of surface material. In 2021, OSIRIS-REx will begin its journey home, arriving at Earth in September 2023. Then it will release its sample return capsule containing a precious cargo of material from a world that may have witnessed first-hand the earliest events in the Solar System. The availability of this sample to Earth-based laboratories will represent a scientific bonanza comparable to the first return of samples from the Moon in 1969.

8. REFERENCES

[1] National Research Council Solar System Exploration Survey. “New Frontiers in the Solar System : an Integrated Exploration Strategy.”, 2003 National Academy of Science

[2] Exploration, Committee On New Opportunities in Solar System. “Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity.” Opening New Frontiers in Space: Choices for the New Frontiers Announcement of Opportunity, n/a 2008.

[3] Nolan, Michael C, Christopher Magri, Ellen S Howell, Lance A M Benner, Jon D Giorgini, Carl W Hergenrother, R Scott Hudson, et al. “Shape Model and Surface Properties of the OSIRIS-REx Target Asteroid (101955) Bennu From Radar and Lightcurve Observations.” Icarus 226, no. 1 (September 2013): 629–40. doi:10.1016/j.icarus.2013.05.028.

[4] Chesley, Steven R, Davide Farnocchia, Michael C Nolan, David Vokrouhlický, Paul W Chodas, Andrea Milani, Federica Spoto, et al. “Orbit and Bulk Density of the OSIRIS-REx Target Asteroid (101955) Bennu.” Icarus 235 (June 2014): 5–22. doi:10.1016/j.icarus.2014.02.020.

[5] Hergenrother, Carl W, Michael C Nolan, Richard P Binzel, Edward A Cloutis, Maria Antonietta Barucci, Patrick Michel, Daniel J Scheeres, et al. “Lightcurve, Color and Phase Function Photometry of the OSIRIS-REx Target Asteroid (101955) Bennu.” Icarus 226, no. 1 (September 2013): 663–70. doi:10.1016/j.icarus.2013.05.044.

[6] Emery, J P, Y R Fernández, M S P Kelley, K T Warden nèe Crane, C Hergenrother, D S Lauretta, M J Drake, H Campins, and J Ziffer. “Thermal Infrared Observations and Thermophysical Characterization of OSIRIS-REx Target Asteroid (101955) Bennu.” Icarus 234 (May 2014): 17–35. doi:10.1016/j.icarus.2014.02.005.

[7] Hergenrother, Carl W, Maria Antonietta Barucci, Olivier Barnouin, Beau Bierhaus, Richard P Binzel, William F Bottke, Steve Chesley, et al. “The Design Reference Asteroid for the OSIRIS-REx Mission Target (101955) Bennu.” arXiv.org, September 2014.

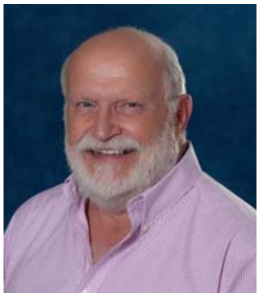
[8] Gaskell, R W, O S Barnouin-Jha, D J Scheeres, A S Konopliv, T Mukai, S Abe, J Saito, et al. “Characterizing and Navigating Small Bodies with Imaging Data.” Meteoritics & Planetary Science 43, no. 6 (September 2008): 1049–61. doi:10.1111/j.1945-5100.2008.tb00692.x.

[9] Brownlee, D E, P Tsou, D Burnett, B Clark, M S Hanner, F Horz, J Kissel, et al. “The STARDUST Mission: Returning Comet Samples to Earth.” Meteoritics & Planetary Science 32 (January 1997): 22.

BIOGRAPHIES

Edward Beshore *is the Deputy Principal Investigator of the OSIRIS-REx asteroid sample return mission and a Senior Staff Scientist at the University of Arizona’s Lunar and Planetary Laboratory. Beshore was a senior engineer at Boeing Computer Services and at Hewlett-Packard. In 2002, he joined the University of Arizona Catalina Sky Survey, a leading NASA-funded program to inventory asteroids and comets that may represent a hazard to the Earth. In 2009, he became the Principal Investigator of the Catalina program. His background in software development and data management is helping him plan and oversee the science operations for the mission when the spacecraft arrives at asteroid Bennu in 2018.*

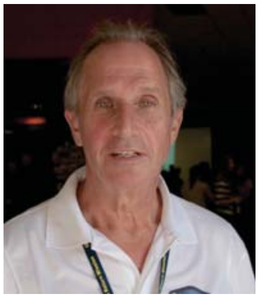
Dante Lauretta *is a professor of planetary science at the University of Arizona’s Lunar and Planetary Laboratory and is the Principal Investigator of the OSIRIS-REx mission. His research interests focus on the chemistry and mineralogy of asteroids and comets as determined by laboratory studies and spacecraft observations. This work is important to understand the chemistry of the early Solar System, the origin of organic molecules that may have led to the origin of life, and the initial chemistry of the Earth and other planets. He is an expert in the analysis of extraterrestrial materials, including lunar samples, meteorites and comet particles. Dr. Lauretta was selected as a Kavli Fellow of the National Academy of Sciences in 2008.*



William Boynton *is the Mission Instrument Scientist for the OSIRIS-REx mission, and is responsible for ensuring that the scientific payloads will be able to make the observations needed to meet mission science requirements. His current research is centered on understanding the role of volatile materials, chiefly water, carbon dioxide and argon, as probes for planetary processes. Boynton has been a team member or instrument PI on Messenger, Mars Science Laboratory, Lunar Reconnaissance Orbiter, Phoenix, Mars Odyssey, and Cassini.*

Jason Dworkin *is currently Chief of the Astrochemistry Branch at NASA Goddard and Project Scientist for the OSIRIS-REx mission. Jason began research into the origins of life at the University of Houston, where he studied amino acids and co-enzymes. He has an A.B. in Biochemistry from Occidental College and a Ph.D. in biochemistry from the University of California, San Diego, where he investi-gated pre-RNA nucleobases. His postdoctoral research at NASA Ames Research Center focused on astrophysical ices. In 2002 he founded the Astrobiology Analytical research group at NASA Goddard Space Flight Center to study extraterrestrial organics.*

David Everett *is currently the Project Systems Engineer for the OSIRIS-REx mission at the NASA Goddard Spaceflight Center. In his 23 years at NASA, he has led the design, build, and launch of three spacecraft, and he was a key player during the launch of three others. He led the technical effort for the Lunar Reconnaissance Orbiter as the Mission Systems Engineer, from design through early-orbit operations. He has received 32 individual awards, 22 group awards; he has published 16 papers; and he co-edited (and wrote the spacecraft design chapter for) the book "Space Mission Engineering: The New SMAD." He earned a BSEE summa cum laude, at Virginia Tech in 1986 and a MSEE at the University of Maryland in 1989.*



Jonathan Gal-Edd *is Ground Segment manager for the OSIRIS-REx mission at the NASA Goddard Spaceflight Center. He is responsible for managing development of the ground system, including coordinating the activities between and among the various ground system elements. He is also responsible for the development of all relevant Interface Control Documents and Operations Agreements, and for pre- and post-mission readiness testing to ensure ground system is ready to support full operations. He represents the ground system at all major mission reviews. Formerly he was the Landsat Data Continuity Mission Ground system Chief Engineer, Ground Systems manager for TDRS-K and Mission Systems Engineering manager for the James Webb Space Telescope (JWST).*

Ron Mink *is the Deputy Project Systems Engineer for the OSIRIS-REx Mission at the NASA Goddard Spaceflight Center. Ron has primary responsibility for the development of the Design Reference Mission, a tool used to plan spacecraft capabilities and ground system operations. Ron received his BSc in Physics from the University of Wisconsin. He was an optical engineer and Deputy Optical Verification Engineer on the James Webb telescope, and Mission Systems Engineer for the GSFC Space Environment Testbeds Project. Most recently, Ron was Ares V Unpressurized Cargo Lead Systems Engineer where he led a team of system and discipline engineers in developing requirements, mission operations concepts, and architectures for launching and operating secondary payload missions on the proposed Constellation Ares V launch vehicle.*

Mike Moreau *has been a member of the Navigation and Mission Design Branch at the Goddard Space Flight Center since 2001. He is currently the Flight Dynamics System Manager for the OSIRIS-REx Mission at GSFC. In that role he is leading the talented team of government and contractor personnel who are responsible for designing and executing the rendezvous and subsequent navigation operations of the OSIRIS-REx spacecraft with the Near-Earth asteroid Bennu. Mike earned MS and Ph.D. degrees in Aerospace Engineering from the University of Colorado, and a BS in Mechanical Engineering from the University of Vermont.*

Chris Shinohara *is the Manager of the Science Processing and Operations Center at the University of Arizona. The SPOC has primary responsibility to support processing of science and navigation data, development of instrument command sequences and observing plans, and data archiving to the PDS. Chris has worked at the UA Lunar and Planetary Laboratory for over 18 years on science mission operations and instrument development for space flight projects. He was involved in the development of the Phoenix Mars Mission Science Operations Center at the UA and the Phoenix Surface Stereo Imager. Previous mission experience includes the Phoenix Mars mission, 2001 Mars Odyssey, Mars '98, Mars Pathfinder, and Mars Observer.*

***Brian Sutter** is the Mission Design Lead for the OSIRIS-REx mission. In his 30 years with Lockheed Martin, Brian has been involved with the design and development of eight successfully-executed inter-planetary missions ranging from MGS to MAVEN. In his current position on OSIRIS-REx, he is responsible for designing the trajectory profile that flies the spacecraft to and from Bennu, and once there, places OSIRIS-REx at the appropriate positions to observe the asteroid and deliver the spacecraft to the sampling site on the surface. He is also actively involved in the Systems Design of the spacecraft to ensure it has the capability to perform the delicate maneuvers required to orbit this small body. Brian earned his BS in Aerospace Engineering from the University of Michigan in 1983.*

DEDICATION AND ACKNOWLEDGEMENT

This paper is dedicated to the memory of Michael Drake, fifth director of the University of Arizona’s Lunar and Planetary Laboratory and first Principal Investigator of the OSIRIS-REx mission. Mike always encouraged us to ask the big questions. We believe that a successful OSIRIS-REx mission will be an enduring monument to his approach to science and to his memory.

We also thank all of the members of the OSIRIS-REx team for their continuing hard work to make this mission a spectacular success. We are privileged to work with you.