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The OSIRIS-REx Mission

Space Environment

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List of Abbreviations

Acronyms

ACS Attitude Control System. 17

ATLO Assembly, Test, and Launch Operations. 15

DEC Double Engine Centaur. 8

FOV field of view. 21, 22

GEO Geostationary Orbit. 9

GN&C Guidance, Navigation and Control. 16, 20

GTO Geosynchronous Transfer Orbit. 9

HGA high-gain antenna. 14, 16, 17, IV

HLV Heavy Lift Vehicle. 7

LGA low-gain antenna. 16, 17

LH2 Liquid Hydrogen. 8

LIDAR Light Detection And Ranging. 20

LO2 Liquid Oxygen. 7

MAVEN Mars Atmosphere and Volatile EvolutioN. 14, 16, 17

MGA medium-gain antenna. 16, 17

MLI multi-layer insulation. 18

MRO Mars Reconnaissance Orbiter. 14, 17

NEO Near-Earth Object. 3

NFT Natural Feature Tracking. 20

OCAMS OSIRIS-REx Camera Suite. 20, 22, IV

OLA OSIRIS-REx Laser Altimeter. 20, 22, 23, IV

OSIRIS-APEX Origins, Spectral Interpretation, Resource Identification and Security – Apophis Explorer. 24

OSIRIS-REx Origins, Spectral Interpretation, Resource Identification, and Security – Regolith Explorer. 1–3, 5, 14–20, 24, 27, IV

OTES OSIRIS-REx Thermal Emission Spectrometer. 20–22, IV

OVIRS OSIRIS-REx Visible and Infrared Spectrometer. 20, 21, IV

PICA Phenolic-Impregnated Carbon Ablator. 16

RExIS Regolith X-ray Imaging Spectrometer. 20, 23, IV

RF radio frequency. 16

RP-1 Rocket Propellant 1. 7

SARA Sample Acquisition and Return Assembly. 15, IV

SDST Small Deep Space Transponder. 16

SEC Single Engine Centaur. 8

SLA Super-Light Ablator. 16

SRB Solid Rocket Boosters. 7

SRC Sample Return Capsule. 14–16, 21, 24, IV

SRS Shock Response Spectrum. 12

TAG Touch-and-Go. 17, 20, 22, 24

TAGCAMS TAG Cameras. 20

TAGSAM Touch-and-Go Sample Acquisition Mechanism. 14, 15, 18, 20, 21, IV

TCM Trajectory Correction Maneuver. 17

TWTA Traveling Wave Tube Amplifier. 16

ULA United Launch Alliance. 7

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1. Introduction

Ever since the launch of the first artificial satellite on October 4^{th} 1957, space exploration and its associated fields have seen immense development; with a myriad of spacecraft, manned and unmanned, being sent to perform space exploration missions which have greatly contributed to humanity's understanding of the cosmos.

The current report was written within the scope of Space Environment to give a thorough description of the Origins, Spectral Interpretation, Resource Identification, and Security – Regolith Explorer (OSIRIS-REx) mission— the first-ever U.S. mission to gather an asteroid sample. This mission marks a critical turning point in space exploration history and provides priceless information about the makeup of asteroids, which are thought to be the building elements of our solar system.

A brief summary of the OSIRIS-REx mission's primary and secondary goals, trajectory, and orbit design are provided in section 2. Gathering and returning a sample from the surface of the asteroid is the main objective of the expedition. Comprehensive surveys of the asteroid's morphology, composition, and geology are among the secondary goals. Other objectives include evaluating possible risks and resources for upcoming space missions. The trajectory design, which includes the intended flight route, important maneuver locations, and the orbital insertion method around the target asteroid, will also be covered in this part.

The mission launch will be covered in detail in section 3, which includes a thorough rundown of the launch phase and launch system. It will include information on the launch vehicle's capabilities and specifications, a description of the events that take place from liftoff to post-launch, and a summary of the initial trajectory modifications needed to put the spacecraft on its course to the asteroid. This section will provide a clear understanding of how the OSIRIS-REx spaceship was successfully launched into space by exhaustively examining major components of the launch system, such as the rocket stages, propulsion techniques, and payload integration.

The analysis of the OSIRIS-REx spacecraft, including its cargo, structure, subsystems, and mission-specific instruments, will be the exclusive focus of section 4. The design and engineering of the spaceship will be examined in this section, with a focus on the structural elements that maintain the spacecraft's integrity and functionality in the hostile environment of space. We'll look at the subsystems, including power, communications, navigation, and thermal control, and how they support the mission's success. The scientific tools and sampling techniques intended to gather and preserve the asteroid sample will be described in full in the payload section. In order to emphasize their crucial significance in accomplishing the mission's goals, the special mission-specific instruments, such as those needed for in-depth surface analysis and navigation in close proximity to the asteroid, will also be covered.

2. Mission Overview

The OSIRIS-REx mission stands as a beacon of human ingenuity and scientific exploration, embarking on a journey to unlock the secrets of our solar system's ancient past. In this comprehensive overview, we delve into the mission's multifaceted objectives, the intricacies of trajectory design, and the meticulous planning behind orbit design, illuminating the path toward groundbreaking discoveries.

Figure 2.1: OSIRIS-REx Mission Logo. [15]

2.1. Objectives

The asteroid Bennu, a carbon-rich remnant of the early solar system that provides a unique insight into the origin and evolution of celestial bodies, is the focal point of the mission. Scientists are hoping to uncover important hints regarding the origins of our solar system and possibly life itself by closely examining Bennu. Bennu's makeup, which is thought to be rich in organic molecules—the building blocks of life—makes it especially interesting.

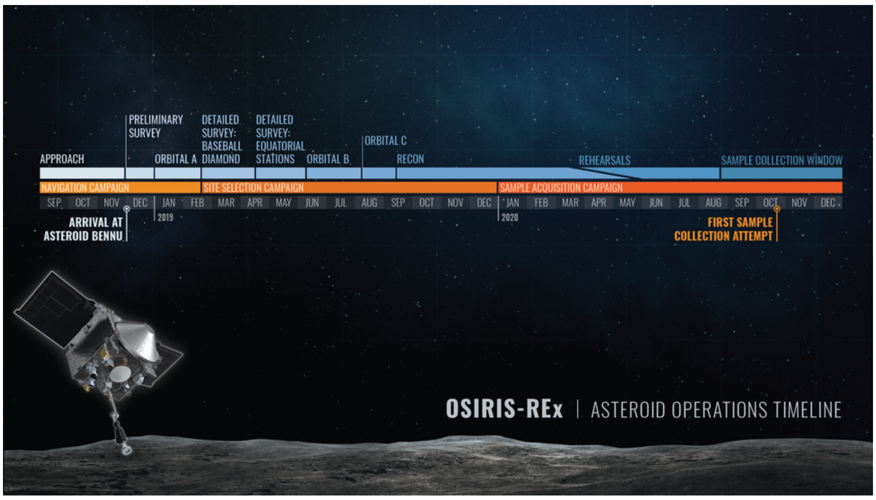


Figure 2.2: A timeline of OSIRIS-REx operations at asteroid Bennu. [31]

One of the primary goals of the OSIRIS-REx mission is to collect a sample of material from the surface of Bennu and return it to Earth for analysis. This sample, expected to be at least 60 grams in size, will provide scientists with unprecedented insights into the composition and history of the asteroid. By studying the sample in detail, researchers hope to unravel Bennu's geological history, understand its formation processes, and uncover clues about the conditions present in the early solar system.

In addition to sample collection, the OSIRIS-REx mission aims to study Bennu's surface in detail, mapping its topography, mineralogy, and composition. To achieve this, the spacecraft is equipped with a suite of scientific instruments, including cameras, spectrometers, and a laser altimeter. These instruments work together to create detailed maps of Bennu's surface, allowing scientists to identify key features and understand the asteroid's geological characteristics.

Furthermore, the mission seeks to investigate Bennu's orbit and trajectory to better understand the dynamics of near-Earth asteroids. Bennu is classified as a potentially hazardous asteroid due to its close approach to Earth and the possibility of future impact events. By studying its orbit and trajectory, scientists can refine their models of asteroid motion and improve predictions of potential impact events, contributing to planetary defense efforts.

Figure 2.3: The sample return capsule from NASA's OSIRIS-REx mission is seen shortly after touching down in the desert, Sunday, Sept. 24, 2023, at the Department of Defense's Utah Test and Training Range. The sample was collected from the asteroid Bennu in October 2020 by NASA's OSIRIS-REx spacecraft. [16]

Behind the OSIRIS-REx mission are a team of dedicated scientists and engineers who have spent years planning and executing the mission's objectives. At the helm is Principal Investigator Dante Lauretta, a leading expert in planetary science and the driving force behind the mission's scientific vision. Assisting Lauretta is Deputy Principal Investigator Heather Enos, who oversees the operational aspects of the mission, ensuring its smooth execution from planning to execution.

2.1.1. Bennu Asteroid

Bennu is a carbonaceous asteroid, meaning it contains a significant amount of carbon-rich compounds, including organic molecules. It is categorized as a Near-Earth Object (NEO), which means it has an orbit that brings it close to Earth's orbit. This makes it a particularly intriguing object for scientific study, as it provides insights into the early solar system and the processes that led to the formation of planets like Earth.

Bennu's comparatively pure state is one of its most remarkable features. It is believed to have material from the early solar system preserved because it is a tiny body with little geological activity. Because of this, it functions as a kind of time capsule that gives scientists an insight into the circumstances and mechanisms that prevailed billions of years ago.

Bennu has a roughly spherical shape and measures about 500 meters (about 1,640 feet) in diameter, making it relatively small compared to other asteroids. Its surface is covered in a layer of loose, rocky material, known as regolith, which is thought to have been created by the continuous bombardment of micrometeorites over millions of years. This regolith is of particular interest to scientists, as it holds clues about the asteroid's history and composition.

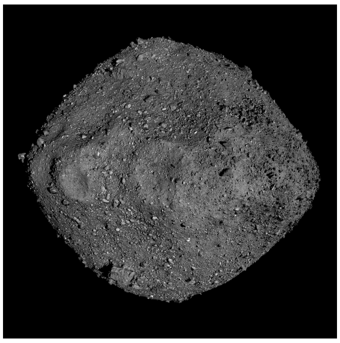


Figure 2.4: Bennu Asteroid's size comparison. [27]

The surface of Bennu also features a variety of geological features, including boulders, craters, and ridges. These features provide valuable information about the asteroid's formation and evolution. For example, the presence of large boulders suggests that Bennu may have experienced a process known as "mass wasting," where material moves downhill due to gravity, reshaping the surface over time.

Scientists are quite interested in Bennu's orbit in addition to its geological aspects. It has a period of roughly 1.2 years and travels in a nearly circular orbit around the Sun. Its orbit is not entirely stable, though, and it periodically approaches Earth. This makes it an asteroid that could be dangerous because there is a remote possibility that it will collide with Earth in the far future. Therefore, analyzing Bennu's orbit and trajectory is crucial to comprehending its long-term dynamics and determining any possible impact hazards.

2.2. Trajectory Design

The trajectory of an asteroid like Bennu is a critical aspect of understanding its behavior, both in the short term and over longer periods. Bennu's trajectory refers to the path it follows as it orbits the Sun, which is influenced by gravitational interactions with other celestial bodies, such as planets like Earth. Bennu follows an elliptical orbit around the Sun, much like the orbits of planets in our solar system. However, its orbit is not perfectly circular, meaning its distance from the Sun varies over time. This elliptical orbit brings Bennu relatively close to the Sun at its closest approach (perihelion) and farther away at its farthest point (aphelion). Understanding how elements like solar radiation pressure, gravitational pull, and the Yarkovsky effect affect Bennu's space travel is essential to studying its journey. The Sun and other planets, including Earth, exert gravitational pull on Bennu, which shapes its orbit and determines its future course.

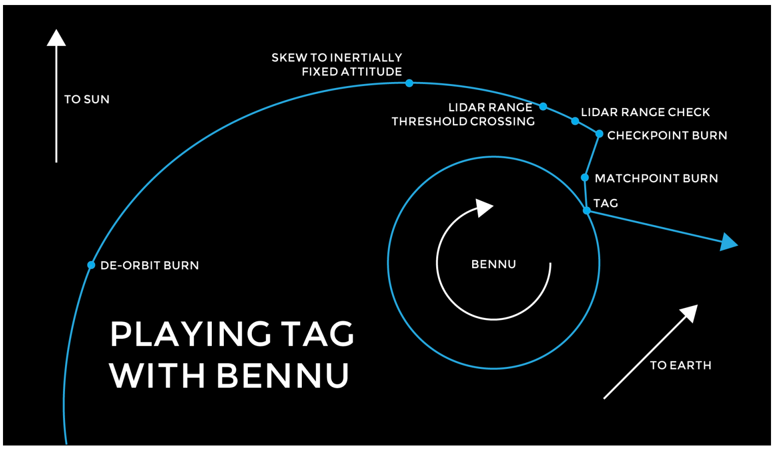


Figure 2.5: Trajectory scheme. [28]

The Yarkovsky effect is a phenomenon where the absorption of sunlight by an asteroid's surface and the subsequent re-radiation of that energy into space creates a tiny but continuous force that can alter the asteroid's trajectory over time. This effect becomes particularly relevant for small bodies like Bennu, whose size and mass make them susceptible to even small perturbations.

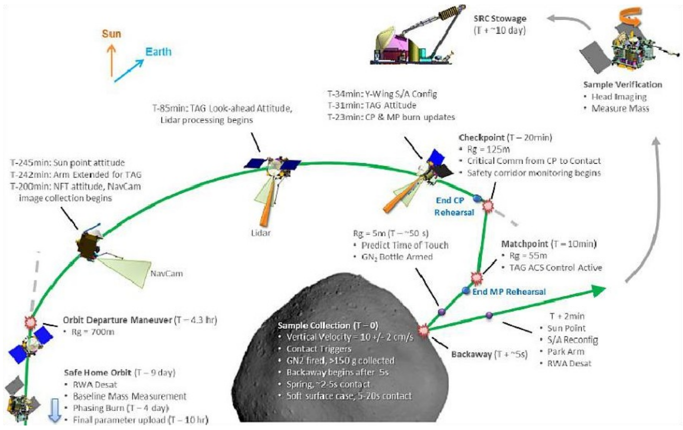


Figure 2.6: Asteroid Landing. [28]

Studying Bennu's trajectory is not only important for understanding its future path through space but also for assessing any potential impact risks it may pose to Earth. By accurately predicting Bennu's orbit and trajectory, scientists can determine the likelihood of a future collision with our planet and take appropriate measures to mitigate any potential threats. Bennu's trajectory comprises its spin axis orientation and rotation in addition to its orbital dynamics. Planning spacecraft missions, like NASA's OSIRIS-REx, which needs precise navigation and maneuvering to approach and study the asteroid, requires an understanding of these elements of its motion.

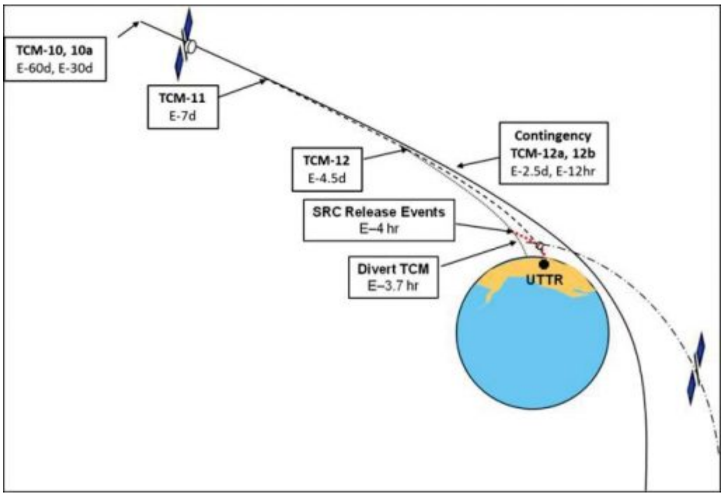


Figure 2.7: Returning to Earth. [28]

2.3. Orbit Design

For missions like NASA's OSIRIS-REx, orbit planning is critical, especially for researching asteroids like Bennu. The mission's main goal was to retrieve samples from Bennu and bring them back to Earth for examination. But reaching this objective necessitated meticulously arranging the spacecraft's orbit and route.

Science is quite interested in the asteroid Bennu itself. As an asteroid of carbonaceous composition, it has elements that are primitive and originate from the early solar system. Scientists are hoping to learn more about the beginnings of our solar system and the components of life on Earth by closely examining Bennu.

The spacecraft's trajectory from Earth to Bennu had to be planned by engineers. This required figuring out the best route to take in order to reach the asteroid while taking orbital mechanics and gravitational forces into consideration. The spacecraft's trajectory needed to make sure it reached Bennu at the appropriate time and location for sampling.

The spaceship had to go into orbit around the asteroid once it was close to Bennu. This meant making precise movements to stay safe while matching Bennu's speed and trajectory. The altitude and inclination of the orbit were carefully selected to suit scientific goals and maintain the stability and safety of the spacecraft.

The orbit design also influenced the selection of sampling sites on Bennu's surface. Scientists identified regions of interest based on factors such as surface composition, terrain, and accessibility. The spacecraft's orbit was adjusted to position it correctly for sample collection, with multiple sampling attempts planned to maximize the chances of success.

Throughout the mission, different orbital phases were utilized for various scientific observations and maneuvers. These included mapping Bennu's surface, studying its composition, and analyzing its geology. Each phase required precise orbital adjustments to achieve the desired objectives while conserving fuel and spacecraft resources.

3. Launch System

3.1. Atlas V Rocket Family

The OSIRIS-REx mission, now OSIRIS-APEx was launched on September 8th, 2018 using Atlas V rocket. This is an expendable launch system operated by United Launch Alliance (ULA). ULA was formed on December 1st, 2006 as a joint venture between Lockheed Martin Corporation and the Boeing Company to provide reliable, cost efficient spacecraft launch services for the U.S. government and commercial costumers [32]. This family of rockets has two major configurations, the Atlas V 400 Series and the Atlas V 500 Series. However, an additional series entitled Atlas V Heavy Lift Vehicle (HLV) was a conceptualized and is shown in Figure 3.1 together with the remaining series.

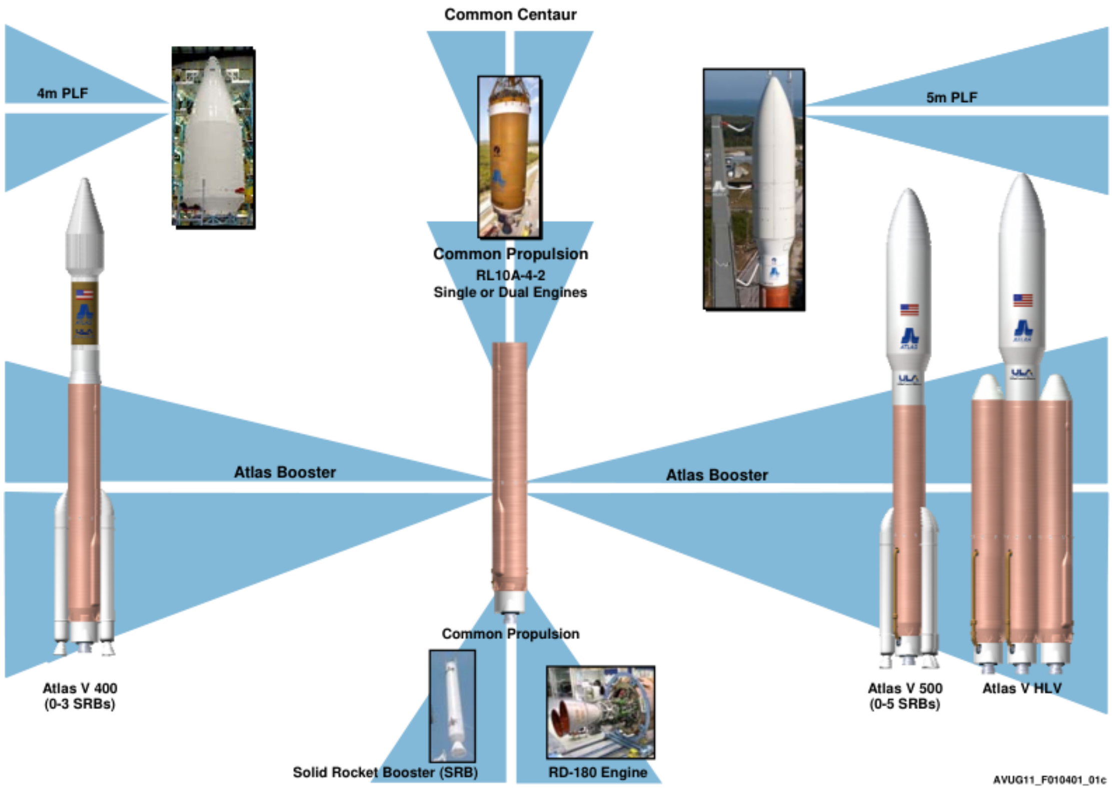
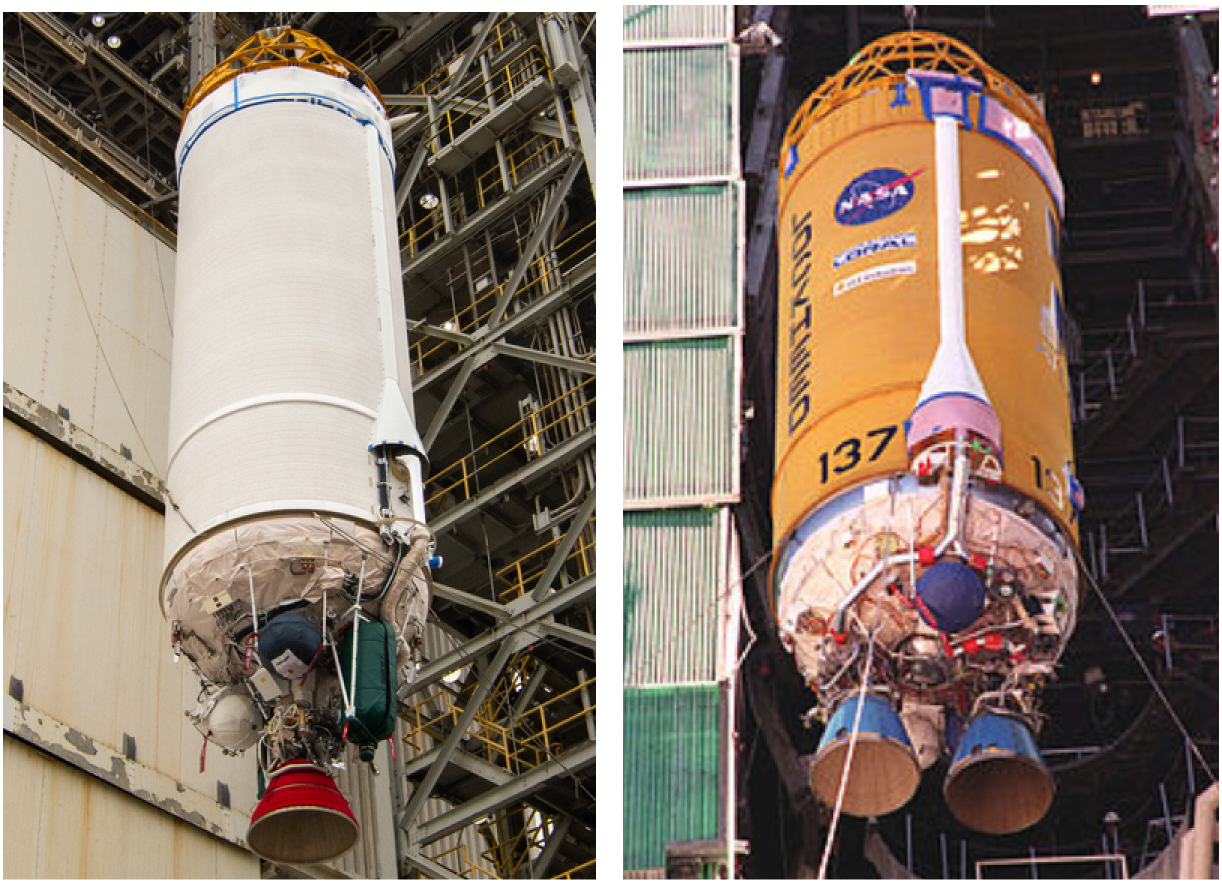


Figure 3.1: Atlas V Rocket family Overall Configuration [32]

The first stage main booster of the Atlas V family rocket, Figure 3.2 uses an RD180 engine with two nozzles powered by Rocket Propellant 1 (RP-1) and Liquid Oxygen (LO2). This engine was manufactured in Russia and designed purposely for the Atlas rocket family. However, following the growing tension in the Crimea region late in the 2010 decade the Atlas V rocket family began to phase out and early in the 2020 decade ULA announced that the rocket family was to be decommissioned following the economic sanctions imposed to Russia for the invasion of Ukraine. None-the-less, several launches remain scheduled using these rocket engines until 2029, 17 launches to be precise, with the most forthcoming launch being the Boeing Starliner crewed mission that is scheduled to take flight on June 1st of 2024. To take account for these launches ULA acquired the engines beforehand making sure the Atlas V delivered all the expected payloads for this rocket family. As of today the production lines for the RD180 engines have been dismantled in Russia. Despite, this geopolitical/historic note, if necessary and depending on the launch system series the main booster can be assisted by zero to five strap-on Solid Rocket Boosters (SRB) that provide additional thrust [32].

Figure 3.2: First Stage Main Booster of Atlas V Rocket Family

Regarding the second stage every series utilizes either a Single Engine Centaur (SEC) Figure 3.3a or a Double Engine Centaur (DEC) Figure 3.3b. Regardless every Centaur configuration utilizes an RL-10 restartable Pratt & Whitney engine powered by Liquid Hydrogen (LH2) and LO2.



(a) Single Engine Centaur

(b) Double Engine Centaur

The centaur stage uses an adapter to fix the payload and the payload fairings which can be chosen from variety of fairings dimensions [32] all having one of two possible diameters. The 4.2m diameter fairing was initially developed for the Atlas II rocket family by General Dynamics Corp, this fairing diameter can be used with a total of three different lengths

9m, 10m and 11m which can accommodate various masses and dimensions of payloads, depending on the mission. The 5.4m diameter fairing was developed for the Atlas V by RUAG Space and is based on a similar flight-proven fairing design from the Ariane 5 Rocket family, this fairing can also be used with a total of three different lengths 20.7m, 23.4m and 26.5m, the major difference is that these fairings accommodate both the payloads of various mass and dimensions and the Centaur stage. Whereas, the 4.2m diameter fairing does not accommodate the Centaur stage, Figure 3.4.

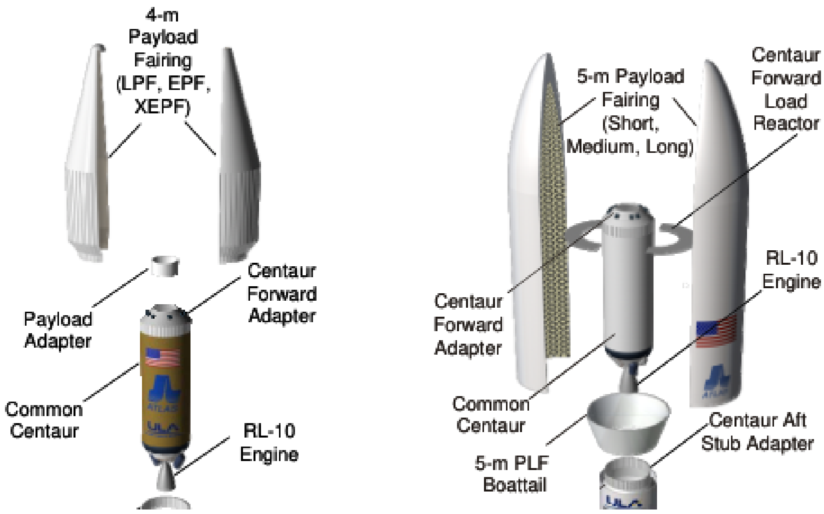


Figure 3.4: Different Payload Fairings for the Atlas V Rocket Family

The major difference between the previously stated Atlas V Series are their payload delivering capabilities. For instance, the capabilities for delivering payloads of certain masses to a Geosynchronous Transfer Orbit (GTO), Figure 3.5 which are transfer orbits with an apoapsis that allows the insertion of satellites in Geostationary Orbit (GEO) where the orbital period is roughly equal to 24h, are shown in Table 1 for each Atlas V Series. The GTO of 1804 $^m/_s$ is an orbit of around 116000 km using Equation 1 which is an example of high earth orbiting satellites such as VELA 1A mission. The GTO of 1500 $^m/_s$ is an orbit of around 170000 km, since the velocity necessary for the centrifugal force to balance the gravitational pull, decreases with height. This orbit is also an example of high earth orbiting satellites such as the TESS mission.

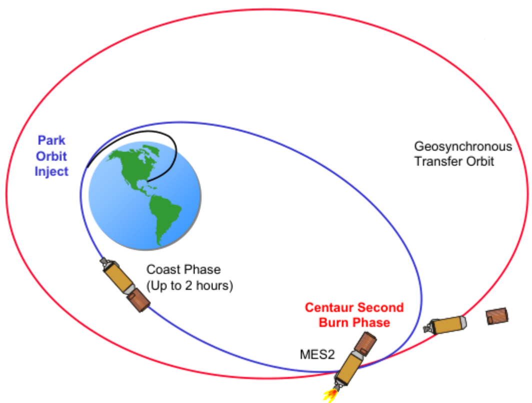


Figure 3.5: Geosynchronous Transfer Orbit.[32]

$$v = \sqrt{\frac{\mu_\oplus}{R_\oplus + h}} \tag{1}$$

Series Number	401	411	421	431	501	511	521	531	541	551
Performance to GTO 1804 (m/s)	4750	5950	6890	7700	3775	5250	6475	7475	8290	8900
Performance to GTO 1500 (m/s)	3460	4450	5210	5860	2690	3900	4880	5690	6280	6860

Table 1: GTO Payload Capabilities of the Atlas V Rocket Family by Series Number in kg[32]

3.2. Osiris-REx Launch System

The Atlas V series utilized to launch Osiris-REx was the series 411, shown in Figure 3.6. Since the series nomenclature for the Atlas V Rocket family uses the first digit to designate the fairing type, the second digit to designate the number of solid rocket boosters and the third digit to designate the number o Centaur RL-10 engines. One can determine that the 411 Series employed in the Osiris-REx mission had a 4.2m diameter fairing, a main booster with one solid rocket booster and a single engine Centaur shown in Figure 3.3a [32] [35].

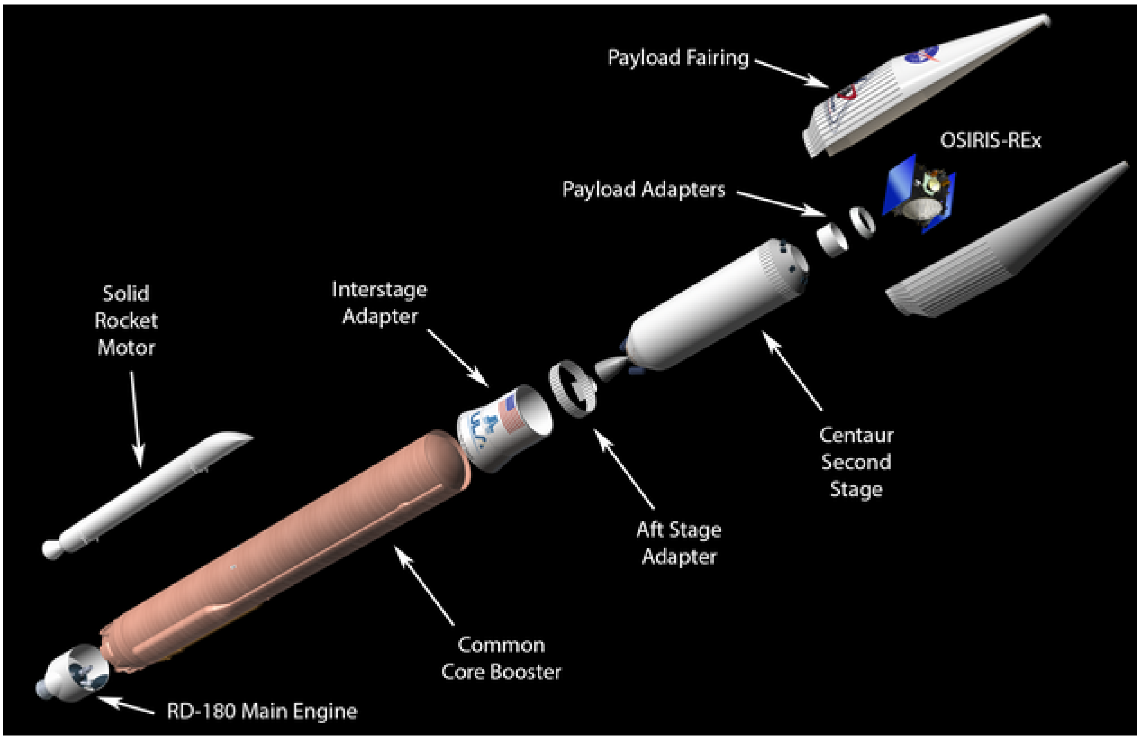
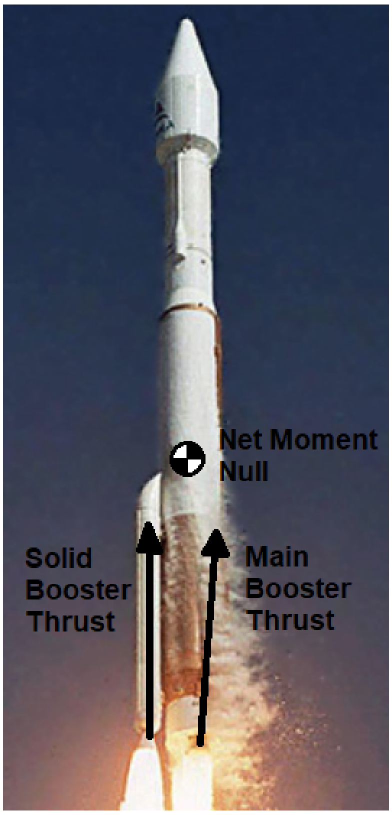


Figure 3.6: Osiris-REx Launch System.[35]

In Figure 3.6 one can verify that the main booster was assisted by one solid rocket booster and that the fairings chosen were the 4.2m diameter ones which did not enclose the Single Engine Centaur stage, knowing that the Osiris-REx mission dimensions were a presumed cylinder with a base diameter of 2.44m and a height 3.15m one can assume that the fairing type which was used was the 4.2m diameter with the 9m length since this information although public is not readily available. This is a two piece shell fairing, Figure 3.7, composed of an aluminium skin with aluminium stringers and vertical structural components [35].Additionally from Table 1 one can see that the capabilities of the 411 Series are 5950 kg to a 1804 $^m/_s$ GTO and 4450 kg to a 1500 $^m/_s$ GTO. Thus we can assume that the Osiris-REx mission is below those masses, in fact the Osiris-REx mission launch mass was 2110 kg.

Figure 3.7: Osiris-REx and the Launch System Fairing.[35]

To perform the deliverance of such payload to space the main booster which employs one RD-180 engine with two nozzles capable of attaining 3800 kN of thrust was assisted by one solid rocket booster capable of attaining an additional 1600 kN thrust, thus the total thrust of the first stage was set at around 5400 kN.The thrust unbalance from launching with only one solid rocket booster which creates a moment around the rocket center of mass which is compensated by the RD-180 two nozzle system which has thrust vectoring capable of turning the nozzles up to 8° and compensates creating an additional opposing moment, Figure 3.8a [25]. The solid rocket booster assists with lift-off and attaining maximum aerodynamic pressure, roughly thirty seconds afterwards it separates from the main booster, Figure 3.8b [36].



(a) Atlas V 411 Thrust Inbalance Compensation

(b) Solid Rocket Booster Separation [36]

The main booster is 3.8m in diameter and 32.5m in height, Figure 3.9a, its tanks are structurally rigid and serve has a structural component of the first stage, they are manufactured from aluminium barrels with aluminium spun formed domes and aluminium inter tank skirts. The solid rocket boosters are developed by Aerojet Rocketdyne they are 1.6m in diameter and 20m in height, Figure 3.9b, its fuel and oxidizer are mixed together into a solid propellant and packed into a solid cylinder, this fuel is ground lit at lift-off and burns until separation from the main booster.

(a) Osiris REx Main Booster [35]

(b) Osiris REx Solid Rocket Booster [35]

3.3. Launch Phase

For a mission of such complexity there are several critical stages in terms of the loads applied to the structure of the Osiris-REx spacecraft. None-the-less, load wise, lift-off is one those stages if not the most critical. The loads applied during lift-off can either make the structure buckle under acceleration or make the structure shake so severely that it might be rendered inoperable if developed incorrectly. From [32] the load case of the launch system are made available. Typically this data is telemetry registered in trial flights. In Figure 3.10 one can see the Shock Response Spectrum (SRS) of the Atlas V Rocket family, the shock response spectrum is a graphical representation of how a single degree of freedom system would react to a certain input, in this case frequency. In Figure 3.10 one can see that the axial acceleration shows a maximum near the 20Hz to 30Hz and the lateral acceleration shows a maximum near the 100Hz region.

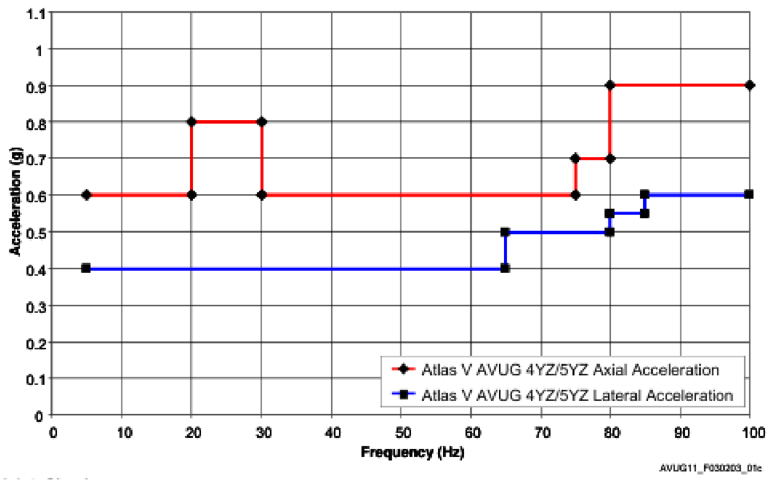


Figure 3.10: Quasi-Sinusoidal Vibration Levels for Atlas V 400 Series and Atlas V 500 Series Based on SRS. [32]

In fact, this data is commonly used to dimension and ground test spacecraft structures. For instance, knowing that the typical frequencies at launch are within the 50Hz to 100Hz frequency range, engineers avoid the design of a spacecraft structure whose first mode of resonance frequency lies within this range of frequencies. Furthermore, another very important data set is the lateral and axial accelerations created during the launch phase, engineers avoid the design of spacecraft structures that may be susceptible to accelerations in this order of magnitude. Thus, these are considered spacecraft design limit load factors and are shown in Figure 3.11

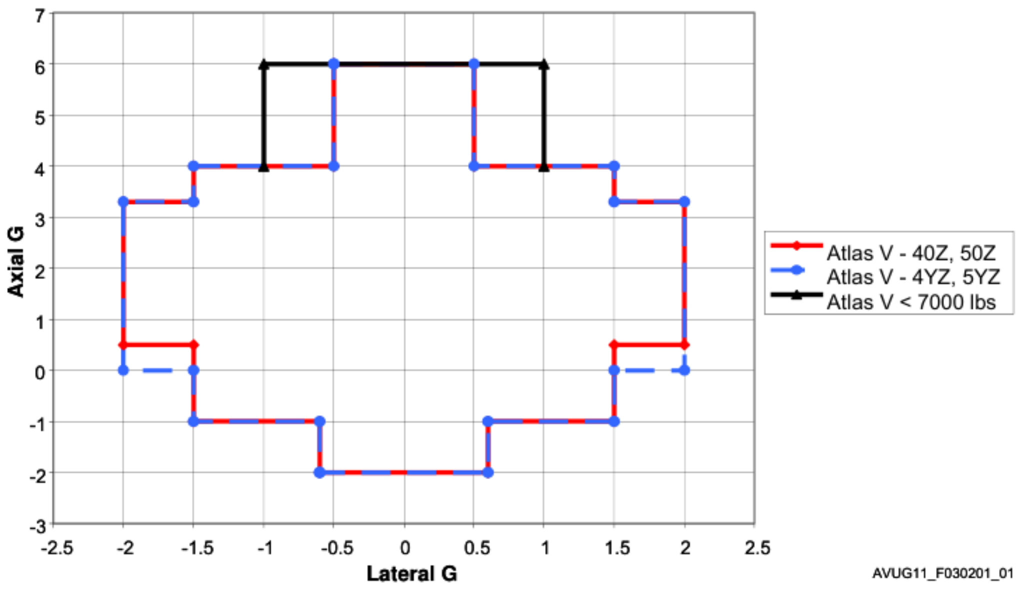


Figure 3.11: Spacecraft Design Limit Load Factors. [32]

Thus, we can assume that the Osiris-REx mission structures load envelope was able to cover all the above shown design limit load factors, meaning that it was able to always withstand more acceleration than the Atlas V rocket was able to create during launch phase. We can also assume that the first mode of ressonance frequency of the Osiris-REx mission was not in frequency range of the launch phase, between 50Hz to 100Hz

4. Spacecraft

The OSIRIS-REx spacecraft fundamentally aims to provide the essential functions necessary to perform an asteroid characterization and sample return mission, while accomplishing the stipulated mission-specific objectives described in section 2.1. Built by Lockheed Martin Space Systems, the spacecraft inherits its key design components for structures and subsystems from previous planetary spacecraft missions - namely, Mars Atmosphere and Volatile EvolutioN (MAVEN), Juno, and Mars Reconnaissance Orbiter (MRO) - incorporating a set of innovative technologies and scientific instruments to both thoroughly characterise asteroid Bennu's physical properties and to provide critical data to support sample acquisition. [2] The sample return capsule itself is a technical and intellectual successor to the Stardust mission, underlining the rich technological heritage of OSIRIS-REx's spacecraft. [4] [12]

Figure 4.1 illustrates the aforementioned spacecraft, fundamentally comprised of the spacecraft bus (which is the main structural component), the Touch-and-Go Sample Acquisition Mechanism (TAGSAM), the Sample Return Capsule (SRC), and the five instruments responsible for remote sensing and scanning the surface of the asteroid. [29] Other notable features defining of its physical profile are the high-gain antenna (HGA), the two 2-axis articulated solar arrays, and the science deck - which contains all science instruments. [4]

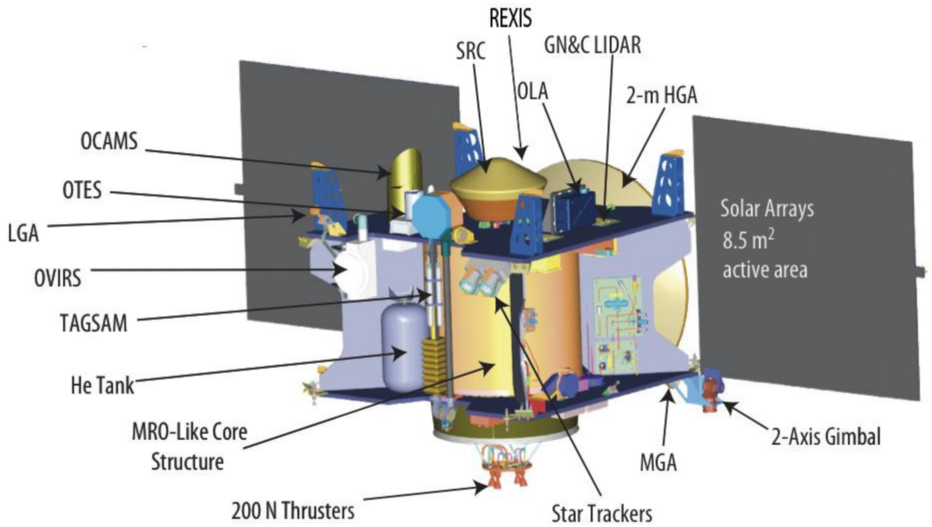


Figure 4.1: Launching configuration of the OSIRIS-REx spacecraft (*in* [29]).

4.1. Structure

The OSIRIS-REx spacecraft structure (see figure 4.2) has a length of 6.2 m with solar panels deployed, a width of 2.43 m by 2.43 m, and a height of 3.15 m when in its stowed launch configuration. It supports a fully fueled launch weight of 2110 kg, 880 kg of which are the dry mass (unfueled). [12]

The main structure is primarily comprised of a 1.3 m diameter cylinder that encloses the main propellant tank, and a cubical satellite platform - made of aluminum-honeycomb core with graphite-composite facesheets - which is radially attached to the core cylinder. [4][29] This structural assembly is used as the foundation upon which all remaining spacecraft equipment is fixed, and its design provides:

1. Enough strength to survive the launch environment;
2. Stiffness to meet the pointing requirements of science instruments;
3. Light-weight support for every other spacecraft component.

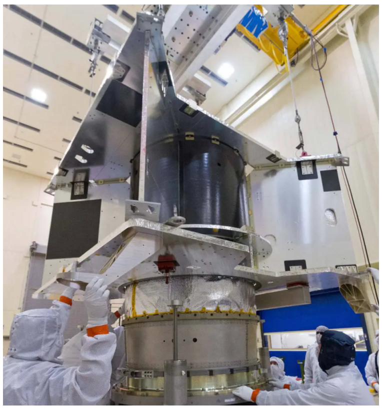
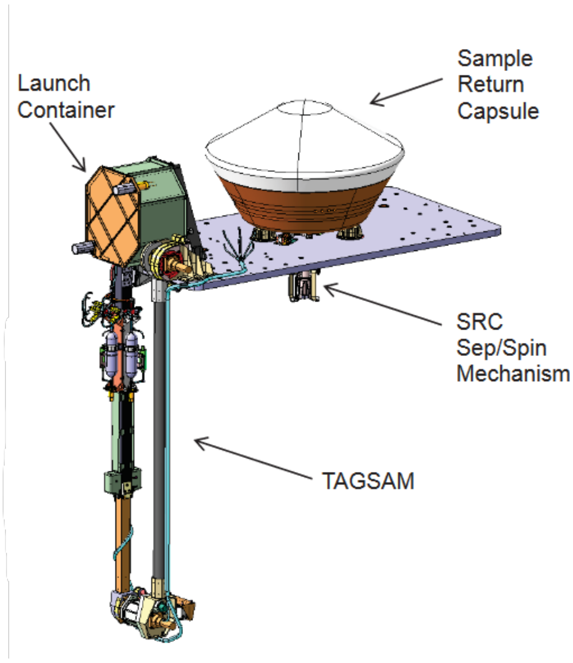
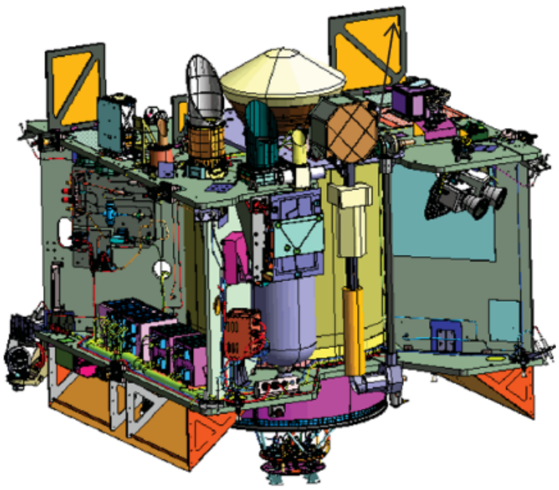


Figure 4.2: Mechanical structure of the OSIRIS-REx spacecraft (*in* [29] and [23]).

A notable sub-assembly of the spacecraft structure is the Sample Acquisition and Return Assembly (SARA) (Fig.4.3). Designed and built by Lockheed Martin, the SARA consists of a simple composite panel structure mounted on the upper deck of the spacecraft; it integrates the Touch-and-Go Sample Acquisition Mechanism (TAGSAM) and the Sample Return Capsule (SRC) into a single unit. Owing to the fact that the SARA was built on a separate plate and earlier during the development, parallel testing was made possible avoiding overtly costly Assembly, Test, and Launch Operations (ATLO). [10] Moreover, as a means of preventing contamination of the TAGSAM head, the SARA was equipped with a launch container (Fig.4.3a) which, from installment until launch, received a continuous nitrogen purge. [4]



(a) CAD model of SARA including the SRC and TAGSAM (*in* [2], p.5, fig.2-4.).



(b) The SARA panel mounted on the upper deck of the spacecraft (*in* [2], p.5, fig.2-3.).

Figure 4.3: CAD models of isolated (a) and assembled (b) SARA.

As mentioned in section 4, the OSIRIS-REx SRC (Fig.4.4) is virtually the same as the one used in the successful Stardust comet sample return mission, with the exception of a few minor changes - namely , updates to the avionics, parachute release system, spring seal, shock mitigation, and the addition of witness plates. Moreover, the Stardust aerogel collector tray was disposed of so as to successfully include the interface that holds the TAGSAM head. [4]

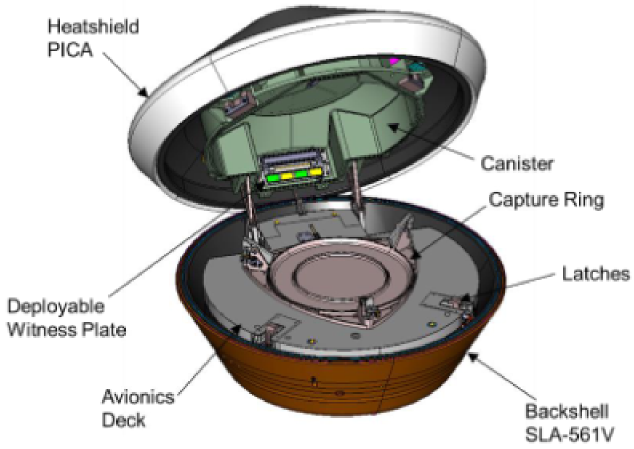


Figure 4.4: Schematic model of the Sample Return Capsule (SRC) (*in* [10], p.5, fig.5).

The SRC uses a monolithic Phenolic-Impregnated Carbon Ablator (PICA) heat shield and the backshell thermal protection material is a Super-Light Ablator (SLA) developed by Lockheed Martin. Other core elements of the SRC are (i) its 3 motors - two of which are used for latches, and a third responsible for opening and closing the heat shield to permit capture of the sample head (ii) an avionics box with G-Switch and pressure-transducer-based trigger used to deploy both the drogue and main chute (iii) the sample canister containing the Bennu sample. [2] [4] [10]

4.2. Subsystems

The OSIRIS-REx flight system is comprised of a series of subsystems designed to ensure the success of an asteroid characterization and sample return mission - notably, attitude control, propulsion, power, thermal control, telecommunications, Guidance, Navigation and Control (GN&C), mechanical devices, and structural support. [2] Figure 4.5 illustrates the flight system block diagram where all subsystems and relevant structural components can be seen.

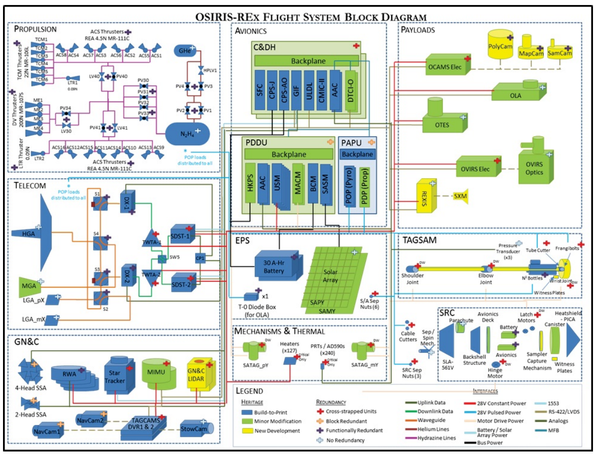


Figure 4.5: Spacecraft block diagram encompassing all subsystems (*in* [2], p.3, fig.2-1).

4.2.1. Telecommunications

The telecommunications system used by OSIRIS-REx is heavily based on the one employed in MAVEN; it includes omni-directional low-gain (LGA), medium-gain (MGA), and directional high-gain (HGA) antennas. Additionally, the system also includes two units of Small Deep Space Transponder (SDST) and 100-W RF Traveling Wave Tube Amplifier (TWTA). [29] The SDST was developed by General Dynamics and NASA's Jet Propulsion

Laboratory and it condenses a plethora of communication functions into a single unit while supporting X-band uplink and X-band and Ka-band downlink communications. [22]

The HGA (Fig. 4.6) is a ≈ 2 m diameter dish with a dual-reflector X-Band system. It supports the majority of the science-data downlink, achieving high data rates of up to 916 kbit/s. [4] [29] Conversely, the circular horn MGA and the pair of choked horn LGAs are used either during operations in which high data rates are not necessary, or when the HGA is unable to be pointed directly at Earth. [4]

Table 2 shows the downlink data rates for each antenna over the course of the mission and for different phases.

Figure 4.6: The HGA and solar arrays installed on the OSIRIS-REx spacecraft (*in* [24]).

Mission Phase	**LGA rates**	**MGA rates**	**HGA rates**
Launch	2000 bps	N/A	N/A
Outbound Cruise	200 bps	N/A	300 kbps
Science Phase	200 bps, TAG: 40 bps	TAG: 40 bps	200 kbps to 916 kbps
Departure	N/A	40 bps	10 kbps to 200 kbps
Return Cruise	40 bps to 10 kbps	40 bps	10 kbps to 300 kbps
SRC Release	10 kbps to 200 kbps		

Table 2: Downlink data rates by mission phase (adapted from [4]).

In precis, within the duration of the mission, the OSIRIS-REx spacecraft will downlink over 165 GBytes of science and optical navigation data, the large majority of which are during asteroid proximity operations. [4]

4.2.2. Propulsion

Much like other systems of OSIRIS-REx, its propulsion system evolved from past successful missions - namely, Mars Reconnaissance Orbiter, Mars Atmosphere and Volatile EvolutioN, and juno - it employs a pressurized mono-propellant design that uses ultra-pure hydrazine. In total, the propulsion system is comprised of 28 engines provided by Aerojet Rocketdyne:

- Four 200 N main thrusters (MR-107S see Fig.4.7);
- Six 22 N Trajectory Correction Maneuver (TCM) thrusters (MR-106L see Fig.4.8);
- Sixteen ≈ 4.5 N Attitude Control System (ACS) thrusters (MR-111G see Fig.4.9);
- Two ≈ 0.5 N specialized low-thrust thrusters (MR-401 see Fig.4.10).

All of which are fed from the central propellant tank housed within the structural cylinder of the spacecraft as mentioned in section 4.1. The tank (Fig. 4.11), made from pure titanium, is pressurized with helium and has a diameter of 124 cm and a height of 150 cm, being able to hold up to 1245 kg of hydrazine propellant. [4] [29]

The four main thrusters are installed on the base of the spacecraft within a single bank in order to be able to produce enough thrust to support the mission's largest and more demanding maneuvers - deep-space maneuvers, asteroid-rendezvous, and asteroid departure. The TCM thrusters are used to control pitch and yaw and correct possible errors during larger main-engine burns. The ACS thrusters are responsible for performing the back-away burn after the Touch-and-Go (TAG); overall, they are mainly used during asteroid operations where precise maneuvering is necessary to maintain proper orientation and trajectory alignment. Lastly, the specialized smallest thrusters are used for ultra-precise maneuvers - namely, during the phasing burn and orbit departure burn at Bennu. [4] [29]

Figure 4.7: MR-107S Engine (*in* [1]).

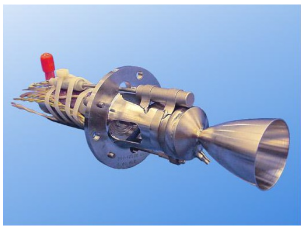


Figure 4.8: MR-106L Engine (*in* [1]).

Figure 4.9: MR-111G Engine (*in* [1]).

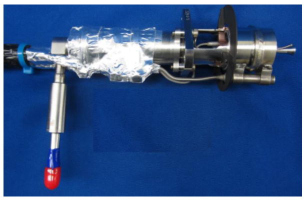


Figure 4.10: MR-401 Engine (*in* [1]).

Table 3 lists relevant data pertaining to the engines used in the OSIRIS-REx mission.

Engine	Thrust (N)	Mass (kg)	Feed Pressure (bar)	Specific Impulse (sec)	Expansion Ratio	Flow Rate (g/sec)
MR-107S	85 - 300	1.01	7 - 35	225 - 236	21.5:1	36.3 - 154.7
MR-106L	10 - 34	0.590	5.9 - 27.6	229 - 235	60:1	4.1 -14.0
MR-111G	1.8 - 4.9	0.33	6.7 - 24.1	219 - 229	N/A	154.2 – 181.4 (g/hr)
MR-401	0.07 – 0.09	0.60	14.8 – 18.6	180 - 184	74:1	0.77 - 2.0

Table 3: Relevant engine data (compiled from [1]).

(a) Propellant tank in a rotation fixture to facilitate ground processing (*in* [29]).

(b) Propellant tank with thermal blanket installation (*in* [30]).

Figure 4.11: OSIRIS-REx main propellant tank.

4.2.3. Thermal

Within the OSIRIS-REx mission, there are two specific considerations which are paramount to the thermal analysis: (i) the TAGSAM head must not exceed 75° and (ii) there must be compliance with temperatures while at the asteroid. Accordingly, maintaining these stipulated adequate temperature ranges was achieved through the use of a conjunction of temperature sensors, heaters, multi-layer insulation (MLI), and coatings. [4] Figure 4.12 shows the spacecraft being lowered into a thermal vacuum chamber with the MLI blanketing installed.

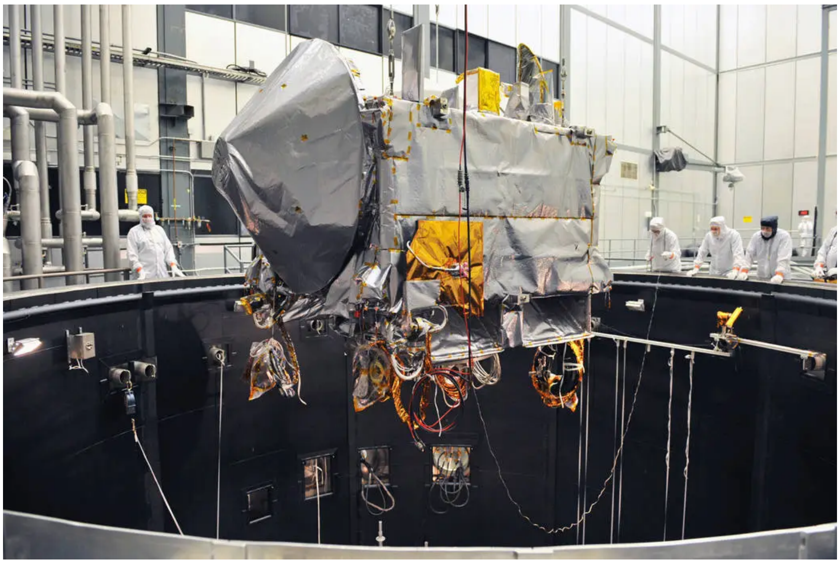


Figure 4.12: The OSIRIS-REx spacecraft being lifted into the thermal vacuum chamber at Lockheed Martin for environmental testing (*in* [8]).

Thermal emissions from Bennu begin to take effect on the spacecraft when the latter approaches the asteroid surface. According to [4], these effects manifest mainly in two ways: (i) the view factor[1] filled by the asteroid reduces the view factor of radiative cooling to deep space, and (ii) the asteroid itself becomes a significant additional heat source, increasing the thermal flux on the spacecraft. Estimating surface temperature distributions across the asteroid's surface was done through development of a thermal model - which demonstrated that, for all asteroid proximity operations, every spacecraft component remained within its allowable temperature threshold. [4]

4.2.4. Power

In sections 4 and 4.1, it was mentioned that the OSIRIS-REx spacecraft possesses two 2-axis articulated solar arrays, which when deployed grant it a span of 6.2 m. The pair of gallium-arsenide solar arrays (Fig.4.13) generate electrical power within the range of 1200 W to 2800 W, depending on solar ranger which will suffer drastic variations through the course of the mission. [4] [29]

Figure 4.13: Illumination testing for OSIRIS-REx solar arrays (*in* [21]) .

The complete power system includes, in addition to the solar arrays, redundant Yardney Technical Products lithium-ion batteries, and avionics. The Li-Ion batteries are used to

[1]Fraction of energy exiting an isothermal, opaque, and diffuse surface 1 (by emission or reflection), that directly impinges on surface 2 (to be absorbed, reflected, or transmitted). [13]

store electrical power, supplying the spacecraft when the solar arrays are not in a sun-pointed attitude - notably, during propulsive maneuvers and sampling events. [4] [29]

4.2.5. Guidance, Navigation and Control (GN&C)

The OSIRIS-REx mission added a layer of complexity to traditionally used GN&C systems due to the need for performing a TAG operation. Accordingly, its GN&C subsystem combines classical deep-space functionalities with specialized equipment required for the proximity phase of the mission. [29]

Classical functionalities are performed by (i) a set of Honeywell inertial measurement units which provide precise rotation measurements (ii) Honeywell reaction wheels, used during attitude maneuvers for precise attitude control (iii) redundant SELEX-EX star trackers, the primary sensors used for attitude determination, and (iv) redundant Adcole sun sensors, which in addition to providing attitude knowledge are also part of OSIRIS-REx's safety system. [4] [29]

The specialized equipment comprises (i) an ASC navigation Light Detection And Ranging (LIDAR) (ii) TAG Cameras (TAGCAMS), and (iii) Natural Feature Tracking (NFT). [4]

The LIDAR systems consists of a 3D flash LIDAR space camera which is used to directly measure surface features and determine the distance to the asteroid while adjusting the magnitude of vector maneuvers.Notably, the LIDAR system required additional developments in the form of radiation sealing in order to endure the radiation environment in deep space over the long course of the mission. [2] [29] The TAGCAMS system is composed of optical cameras which give imaging of both Bennu's surface and background stars within short integration times. This system is used to provide optical back-up to the GN&C LIDAR during TAG. [10] Lastly, NFT works complementarily with the TAGCAMS system as a means of fully backing-up the GN&C LIDAR - this is achieved by using the TAGCAMS to identify known features of Bennu's surface obtained from early observations in order to develop a model of the surface of the asteroid, which is then redirected to the spacecraft and used by the flight system to adequately navigate during the TAG operation. [10]

4.3. Payload

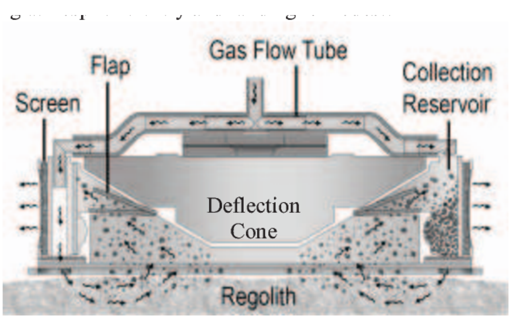
The OSIRIS-REx spacecraft's payload essentially comprises six elements - the Touch-and-Go Sample Acquisition Mechanism (TAGSAM) and the five instruments responsible for remote sensing and scanning the surface of the asteroid (i) OSIRIS-REx Visible and Infrared Spectrometer (OVIRS) (ii) OSIRIS-REx Thermal Emission Spectrometer (OTES) (iii) OSIRIS-REx Camera Suite (OCAMS) (iv) OSIRIS-REx Laser Altimeter (OLA), and (v) Regolith X-ray Imaging Spectrometer (RExIS).

4.3.1. Touch-and-Go Sample Acquisition Mechanism (TAGSAM)

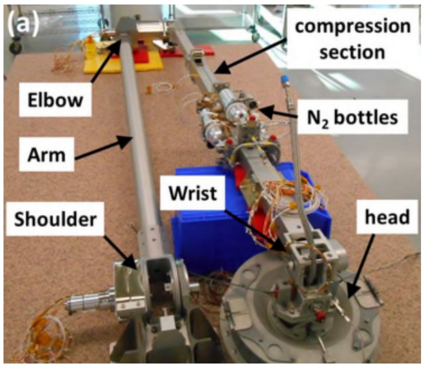
Hitherto, the Touch-and-Go Sample Acquisition Mechanism (TAGSAM) has been extensively mentioned but never fully expounded upon; as such, the present section aims to give an overview of its design and functionalities.

The TAGSAM (Fig.4.14) was developed as an approach to tackle the TAG operations of the mission, which involve brief contact between the spacecraft and the target followed by a swift retreat into a safe area. This type of design, as per [4], aims to minimise contact time, reduce sample handling complexities near-surface, avoid the need for long-term communications with Earth, and reduce the variability of thermal states upon contact with the target. The TAGSAM was the device able to satisfy all of the previous sample-acquisition requirements.

The TAGSAM device comprises two essential components, a single-plane, articulated positioning arm and a detachable sampler head. Contact with the surface is performed solely by the sampler head (Fig. 4.14a), which injects high-purity nitrogen (stored in three bottles to facilitate up to three TAG attempts) into Bennu's surface fluidizing the regolith which is then captured by the head and transported into the SRC sample container. [7] [11] The articulated arm (Fig.4.14b) is responsible for maneuvering the sample head, it is able to position the head for collection up to two metres directly beneath the spacecraft structure, bring it into a viewing position for visual documentation, and finally place it within the SRC. [7] [29]



(a) Schematic of the TAGSAM operation (*in* [6], p.3, fig.2).

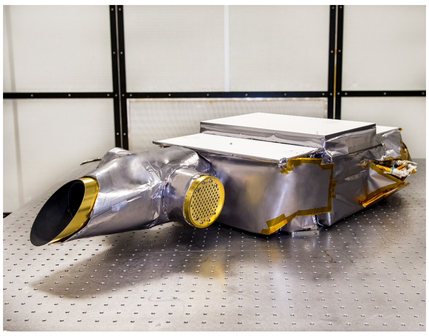


(b) The TAGSAM hardware (*in* [4], p.21, fig.16).

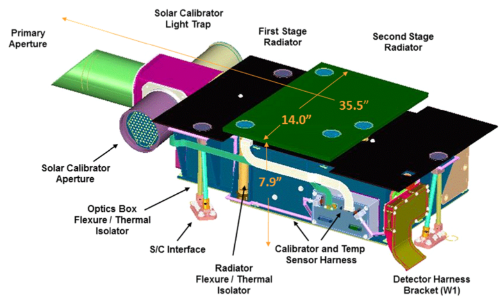
Figure 4.14: The TAGSAM assembly.

4.3.2. OSIRIS-REx Visible and Infrared Spectrometer (OVIRS)

The OSIRIS-REx Visible and Infrared Spectrometer (OVIRS) (Fig.4.15) is a linear-variable point spectrometer with a 0.23° field of view (FOV), covering wavelengths within the interval $[0.4, 4.3]\,\mu$m. It has two main assemblies (Fig.4.15b), one containing the aperture, optics, and detector; the other containing second houses the control electronics. [4] [10] Data collected from OVIRS contains spectral data, global spectral maps (with 20-m resolution), and local spectra information pertaining to the sample site (with 0.08 to 2 m resolution), all of which will provide information on Bennu's composition - namely, mineralogical and molecular components such as carbonates, silicates, sulfates, oxides, adsorbed water, a myriad of organic species, and products of space weathering [26] - allowing for the mapping of its surface composition and subsequent identification of regions of interest for sample collection. [7]



(a) The OSIRIS-REx Visible and Infrared Spectrometer (OVIRS) (*in* [19]).

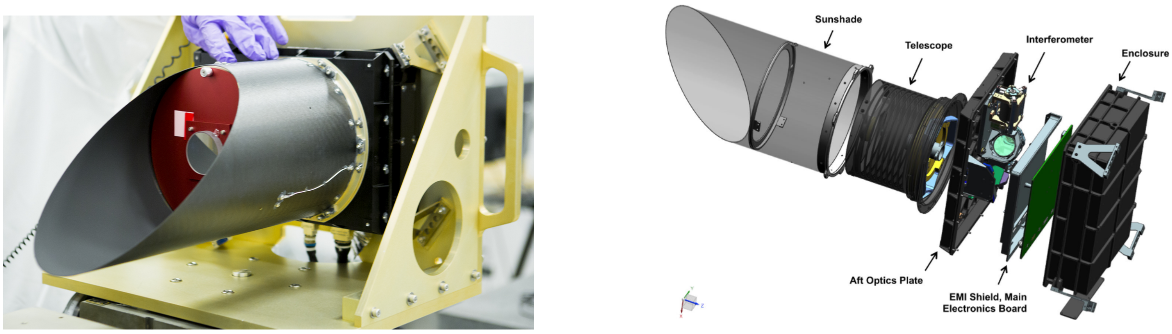


(b) OVIRS schematic model with names and placements of external components (*in* [26], p.9, fig.2).

Figure 4.15: The OSIRIS-REx Visible and Infrared Spectrometer (OVIRS).

4.3.3. OSIRIS-REx Thermal Emission Spectrometer (OTES)

The OSIRIS-REx Thermal Emission Spectrometer (OTES) is a Fourier-transform-interferometer point spectrometer with a 0.46° FOV, covering wavelengths within the $[5, 50]\,\mu$m with 10cm^{-1} resolution. The optics, detector, and control electronics are all contained in a single assembly. [4][10] The resulting measurements from OTES are the same as the ones from OVIRS, however ,in addition to mapping the mineral composition of Bennu, the data acquired from OTES will allow for determination of thermal properties of the asteroid - notably, thermal inertia of surface rocks and soils - all of which are crucial for locating optimal regions for sampling. [4] [5]



(a) The OSIRIS-REx Thermal Emission Spectrometer (OTES) (*in* [33]).

(b) OTES CAD model showing major elements of the modular design (*in* [5], p.6, fig.2).

Figure 4.16: The OSIRIS-REx Thermal Emission Spectrometer (OTES).

4.3.4. OSIRIS-REx Camera Suite (OCAMS)

The OSIRIS-REx Camera Suite (OCAMS) (Fig.4.17) comprises three separate single-string cameras controlled by a fully-redundant control electronics box. The PolyCam is a long-range camera used for both optical navigation and high-resolution imaging of Bennu's surface. It has an aperture of 630 mm, f/3.15, and a 0.8° FOV. [7] [10] The MapCam has an aperture of 125 mm, f/3.4, a 4° FOV, and it is equipped with a four-color filter wheel which allows for the obtainment of wide-band spectrophotometric observations, as well as color imagery of Bennu's surface. As its name may indicate, the MapCam is used for global mapping being responsible for most of the provided mapping images; additionally, it is also used for sample-site reconnaissance. [4] [7] [10] The SamCam has the largest FOV with 22° in order to fully capture the sample collection event during the TAG operation, it captures three images every 5 seconds with an aperture of 24 mm, and f/5.5. [4] [10]

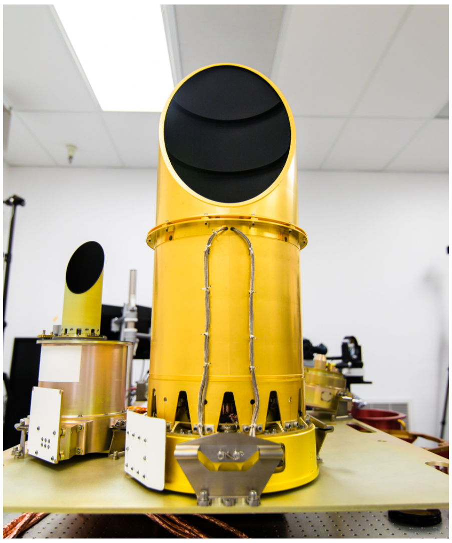


Figure 4.17: The OSIRIS-REx Camera Suite (OCAMS): PolyCam (center), MapCam (left), and SamCam(right) (*in* [34]).

4.3.5. OSIRIS-REx Laser Altimeter (OLA)

The OSIRIS-REx Laser Altimeter (OLA) is a two-axis scanning laser altimeter used to obtain high-resolution topographical information of Bennu's surface. Operating at 1064 nm and covering ranges within [0.5, 7] km, the OLA consists in two assemblies: an electronics box which stores collected data, and a sensor head which contains two lasers transmitters. [20] The high-energy laser transmitter is able to (i) achieve high spatial resolution (ii) support Radio Science, and (iii) provide scaling information for images and spectral spots. Moreover, the low-energy transmitter is able to provide local maps for possible sample sites, as well as generate a global topographic map of Bennu. [7][10]

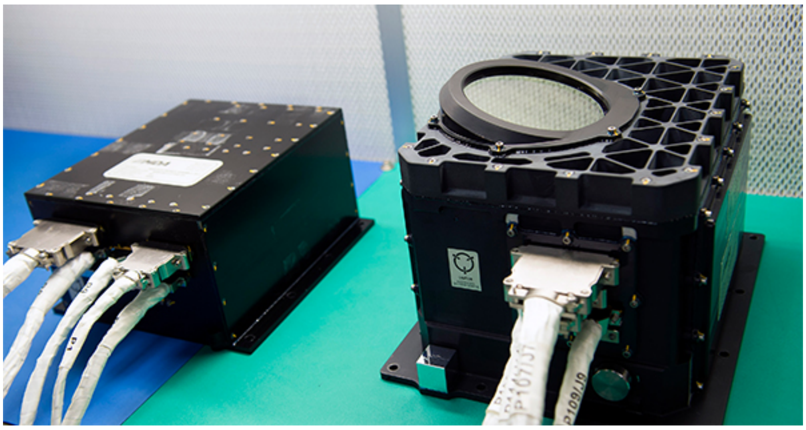
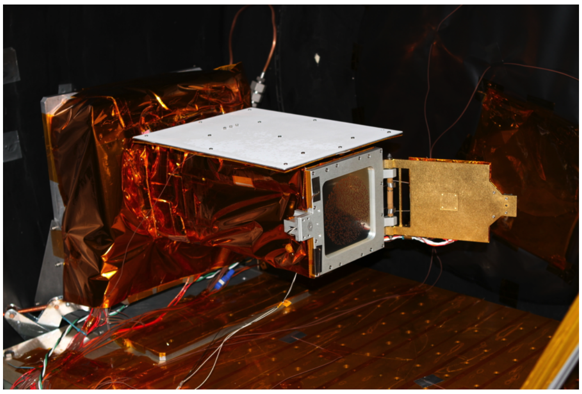


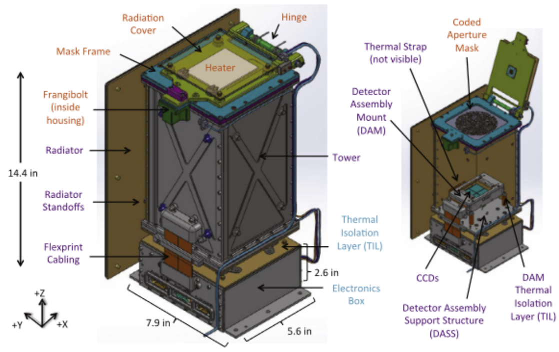
Figure 4.18: The OSIRIS-REx Laser Altimeter (OLA) and its two assemblies (*in* [20]).

4.3.6. Regolith X-ray Imaging Spectrometer (REXIS)

The Regolith X-ray Imaging Spectrometer (REXIS) (Fig.4.19) is an X-ray spectrometer that covers energies within a range of [0.5, 7.5] keV. Built as a collaborative effort between the Massachusetts Institute of Technology and Harvard Smithsonian Center for Astrophysics, REXIS allows for the obtainment of a X-ray ,map of elemental abundance on Bennu - a feat achieved through the observation of the X-ray fluorescence of elements. REXIS is comprised of two assemblies (i) the main spectrometer (Fig.4.19b) - consisting of an electronics box, a tower, and a coded-aperture mask [14] - and (ii) a monitor of the solar X-ray flow. [4] [7] [10]



(a) The Regolith X-ray Imaging Spectrometer (REXIS) (*in* [29]).



(b) Detailed views of the REXIS main spectrometer with sub-assemblies grouped by color (*in* [14], p.7, fig.3).

Figure 4.19: The Regolith X-ray Imaging Spectrometer (REXIS).

5. Concluding Remarks

In precis, the OSIRIS-REx mission was successful in collecting a regolith sample from near-Earth asteroid Bennu and returning said sample to Earth. Over the course of the seven year mission, the OSIRIS-REx spacecraft took several high-resolution pictures of the Earth and Moon, and upon encountering Bennu provided detailed imaging of the asteroid's shape and surface features. The arrival on Bennu allowed for the mapping of its surface, selection of the sample site "Nightingale", and collection of the sample through the Touch-and-Go (TAG) maneuver; indeed, the collected sample quantity of Bennu's surface material far surpassed that of the initial mission requirement (60 grams) with 121.6 grams being acquired. [3] [18]

The OSIRIS-REx spacecraft reached Earth on September 24^{th} 2023, where the Sample Return Capsule (SRC) separated from the spacecraft and entered the Earth's atmosphere, landing in the Utah Test and Training Range where it was retrieved by scientists. The remaining spacecraft did not land back on Earth, instead continuing on to rendezvous with the near-Earth asteroid Apophis on April 13^{rd} 2029 effectively transitioning into a new mission - the Origins, Spectral Interpretation, Resource Identification and Security – Apophis Explorer (OSIRIS-APEX) - which aims to study the physical changes to Apophis resulting from its future close encounter with Earth. [17] [18]

The collected Bennu sample is still being subject to a variety of scientific examinations and analyses, and it most likely will remain under this state for the foreseeable future. Nevertheless, preliminary examination procedures have shown that the sample's composition is dominated by hydrated silicates, sulfides, magnetite, phosphates, and abundant organic matter, as well as other minor/trace phases. [9]

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Appendix A. Individual Contribution

Student	**Report**	**Evaluation**
Inês Sousa	Introduction Spacecraft: - Structure - Subsystems - Payload Conclusion General Report Organization and Structure	100 %
João Gaspar	Introduction Mission Overview: - Objectives - Trajectory Design - Orbit Design	100 %
Miguel Costa	Launch System: - Atlas V Rocket Family - OSIRIS-REx Launch System - Launch Phase	100 %