Colorado School of Mines

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Mars Moon Resource Mission

DREAM

Deimos **R**esource **E**xploration and **A**nchoring **M**ission

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Abstract

The Deimos Resource Exploration and Anchoring Mission (DREAM) is an exploratory mission that aims to evaluate the resource potential and engineering challenges of the Martian moon Deimos for future in-situ resource utilization. DREAM will analyze Deimos's composition and structure using spectrometry instruments to observe the moon's surface and the implanted shaped-charge's ejecta plume. Other instruments will be used to map and image the surface of Deimos, as well as aid in selecting sites for anchoring and shaped-charge implantation. Deimos' interior structure will be analyzed through a seismic study utilizing the shaped charge as a source. Anchoring, a critical technology for resource utilization in low-gravity and rubble-pile bodies, will be demonstrated with micro spine grippers and regolith aggregate binding. The streamlined payload and technology demonstrations meet NASA's Discovery program cost caps while gaining critical insights into Deimos' formation, composition, structure, and relevance for human space exploration. For resource mapping and utilization missions, DREAM offers substantial scientific and technological returns on a focused budget.

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Scientific Background

Phobos and Deimos are the two moons that orbit around Mars. Similar to Earth's moon, these moons always show the same side to Mars and are small and lumpy in shape ("Overview | Mars Moons" n.d.). While these moons are both similar in some respects, there are some individual features that make them each unique. These differences will be studied, as well as the possible formation theories of the moons and the resources that they could yield.

Phobos

Phobos (Figure 1) is the larger of the two Martian moons at 27 by 22 by 18 km ("Overview | Mars Moons" n.d.; "In Depth | Phobos" n.d.). An orbit is completed three times a day at a distance of 6,000 km above the Martian surface. Phobos orbits Mars closer than any other known moon. This is likely because Phobos is on a collision course with Mars, moving closer at a rate of 1.8 m every hundred years. This means Phobos will either crash into Mars in approximately 50 million years, or it will break up into a ring. Phobos has a circular, low inclination, prograde, and equatorial orbit with a location just outside the Martian Roche Limit (Sercel et al. 2018). The moon tidally evolved since formation. There is no atmosphere present and the moon experiences extreme temperature variations ranging from -112 °C on the dark side to -4 °C on the sunlit side ("In Depth | Phobos" n.d.). One of Phobos' most defining features is Stickney crater, which is 9.7 km wide (9 km diameter) and was caused by a giant impact. Additionally, Phobos has groves and ridges, as well as streaks of red and blue material on the surface. The surface of the moon has been powdered by meteorite impacts over time, which have caused landslides that mark the slopes of craters. Phobos has a low albedo of ~7% and a low density of 1.87 g/cm^3, well below the standard density of coherent rock (Sercel et. al 2018). Images of Phobos show that there are fairly large boulders on the surface of ~40-60 m, and the moon likely has a highly porous rubble pile structure.

Figure 1: Image of Phobos taken from NASA's HiRISE camera on MRO ("In Depth | Phobos" n.d.).

Deimos

Deimos (Figure 2) is the smaller of the two Martian moons at 15 by 12 by 11 km (“Overview | Mars Moons” n.d.; “In Depth | Deimos” n.d.). An orbit is completed every 30 hours. Deimos has a circular, low inclination, prograde, and equatorial orbit with a location just outside Mars synchronous orbit (Sercel et al. 2018). The moon tidally evolved since formation and is moving outwards. While Deimos’ surface is heavily cratered, the largest crater is only 1/5 the size of Stickney crater on Phobos and comes in at 2.3 km in diameter (“In Depth | Deimos” n.d.). The surface is expected to have a thick regolith, with a depth that could be up to 100 m. This is due to impact cratering, as well as from dust being redeposited on the surface. While the minimal gravity on Deimos is not enough to keep the dust from impacts on the moon’s surface, the gravity from Mars helps to retain a debris ring around the planet in the region that Deimos orbits. As the moon orbits Mars, the dust is returned to the surface. Deimos has a low albedo of ~7% and a low density of 1.47 g/cm^3, well below the standard density of coherent rock (Sercel et. al 2018). Images of Deimos show that there are fairly large boulders on the surface of ~40-60 m, and the moon likely has a highly porous rubble pile structure.

Figure 2: Enhanced-color image of Deimos taken from NASA's HiRISE camera on MRO ("In Depth | Deimos" n.d.).

Formation Theories

There are numerous theories for the formation of the Martian moons, with none of them being widely accepted. Many theories are based on limited data and models which themselves are based on limited data. However, there are a few theories that are favored and argued by the community. This includes asteroid capture and formation through a circum-Mars accretion disk (Sercel et al. 2018: Ramsley and Head 2021).

First looking at asteroid capture, while there is favor for this theory, many agree that capture is unlikely (Sercel et al. 2018: Ramsley and Head 2021). This is largely based on the orbit characteristics of the moons. However, it cannot be ignored that there are some attributes of the moons that resemble asteroids. There are surface spectra from both moons that resemble C- or D-type asteroids (Ramsley and Head 2021). This is also supported by the bulk densities and morphologies of Phobos and Deimos. Additionally, surface spectra also show signatures that could be phyllosilicates that are commonly found on various asteroids. However, when attempting to model the capture and subsequent orbit stabilization up to present day, there are some challenges. The models must end with the current near-zero eccentricities, near-equatorial inclinations, and close proximities to Mars. While there are carefully selected and adjusted models, the initial conditions are still unlikely. Another challenge to overcome is the fact that Phobos is moving inwards towards Mars. Computations have implied that it is more likely that Phobos has always orbited Mars based on moon's descenoiding altitude. While Deimos is not on a collision course, its orbit is not consistent with any realistic capture mechanisms, meaning that it is more unlikely that Deimos was captured than Phobos. A final challenge is considering when each moon was captured relative to the other. If they were captured at separate times, then the possibility of intersecting orbits and a collision is likely. Specifically, a collision with Deimos is very likely if Phobos was captured after Deimos. Despite spectral results and other characteristics that are similar to asteroids, coinciding the present-day orbits and their traits with asteroid capture models is a challenge and unlikely.

Next, when considering circum-Mars accretion disks, there are three theories on how these disks came to form: (1) primitive asteroids collided and broke up in the Mars Hill sphere (Sercel et al. 2018), (2) a disk of mostly projectile material formed after a large impact with Mars (Sercel et al. 2018: Ramsley and Head 2021), or (3) formation occurred in the early solar system from a primordial circum-Martian disk (Ramsley and Head 2021). One issue with the first theory is that a collision in the Mars Hill sphere is dynamically improbable. However, an advantage behind this theory is that the disk could be tidally evolved into a circular and equatorial orbit. This advantage can also be seen with the second theory as well, which does have the issue of the moon's low albedo not being consistent with Martian material. One difference to note between these theories is the amount of heating expected of the disk material. Significant heating would be expected in the case of an impact, which would alter primitive projectile material, increase albedo, and result in loss of organic material and volatiles. In the case of an asteroid collision, the phyllosilicate-bound water of organics could be preserved, and the low albedo could lead to less hydrated silicate damage of the original material. One characteristic shared by theories two and three are that several large moons would be produced with a total mass that significantly surpasses that of Phobos and Deimos. However, the same model predicts that many of these moons would deorbit Mars over time and could leave only Phobos and Deimos remaining, as well as predicts their present-day orbits. An issue that does appear with the third theory is that dating Phobos' orbital decay back in time leads to starting times that post-date the solar system's formation. For this reason, Ramsley and Head state that an impact to Mars is more likely the cause of formation over the co-accretion theory.

Resources

When considering the resources that could be seen on each moon, it can be highly dependent on which formation theory is favored. Only accretion-disk theories one and two will be compared here (Sercel et al. 2018). If the favored theory is a collision in the Mars Hill sphere between volatile-rich primitive asteroids, then resource and ISRU potential would depend on the abundance of common materials in primitive asteroids, some of which are carbon-rich organics, iron oxides, and hydrated phyllosilicates. Volatiles likely have a lower abundance potential due to formation processes such as shock, heating, and collisional evolution. However, a major resource could be phyllosilicates that survived. This could lead to resources, such as hydrogen and oxygen, organics from carbon compounds, iron oxide, and mafic silicates. Some of the mineralogy from this formation theory would also result in silicates that are not bound as strongly, leading to easier processing and extraction. If the favored theory is a large impact with Mars, then the mineralogy would consist of material from the Martian crust and shallow mantle. This material is majorly mafic silicates and projectile material that would be thermally altered. Heating during the process means that the moons would not be hydrated but would contain high-temperature iron- and magnesium-rich silicates and dehydrated and metamorphosed phyllosilicates.

Concept Definition

The DREAM mission initially started with the task to "[develop] a resource prospecting mission of the Martian Moons. The mission goal is to advance knowledge of resources found on the Martian Moons from their current state toward a reserve. The mission will improve our knowledge of the resource such that the resource could eventually be used to support an activity in space" (from Guide to SPRS 591, Space Resources Projects I, Fall 2023). From this statement, an initial mission concept was created, and the considerations are summarized in the following sections.

Resource Assessment/Brainstorming

One of the first tasks undertaken was to create a list of potential resources that could be utilized from the Martian Moons and then try to prioritize them according to which resources will be utilized first. The list includes:

- **Water:** the use of water is extremely valuable within the space travel context. Water can be used to support human exploration or be divided into hydrogen and oxygen and used as rocket fuel. Evidence for large quantities of water on the Martian moons is scarce, however, and difficulties in separating it from the regolith are relatively unknown.
- **Propellent Storage:** Because Mars has a 25-degree axial tilt, and both moons orbit close to Mars' equatorial plane (1.093 degrees and 0.93 degrees for Phobos and Deimos respectively), the Moons effectively experience seasonal variations along with Mars. This means there are extended periods (approximately 10 months) of complete shadow, and extreme cold, that would be ideal for storage of volatile propellants.
- **Mining Testbed:** Recent missions, including OSIRIS-REx and Hayabusa2, have shown that asteroid mining techniques are in need of development. This is particularly true in ultra-low gravity environments on cohesionless bodies. The moons of Mars are ideal for the development of these mining techniques because they are relatively large and have enough gravity to potentially simplify the problems of mining from cohesionless surface.
- **Raw minerals:** Similar to other bodies, the Marian moons could be used for extraction of minerals for processing into usable commodities, such as aluminum and iron ores. There remain unanswered questions about what minerals are available and how they would be utilized.
- **Bulk Regolith:** Bulk regolith could be used as aggregate for various in situ construction techniques or radiation shielding.
- **Mars Staging Area:** As human exploration of Mars begins, mission architectures have been proposed use the Martian moons as a staging or support facility. The moons possess favorable solar, surface visibility, and delta-V requirements. Traveling to and from the moons' surfaces will be technically simpler than the surface of Mars because they have less gravity and no atmosphere. Real-time communication for Martian rover teleoperation are also possible.
- **Sandbraking**: Researchers have suggested that releasing sand from Mars' moons in front of an aeroshell would densify Mars' atmosphere and increase its slowing capability. The reduction in propellant required for landing would be more than the propellant required to lift the sand from the moons' surfaces (Arias, De LAS Haras, 2019).

The authors believe that the first resources to be utilized from the moons of Mars will be in the service of Mars exploration, the next will be a low-gravity mining testbed, and finally the mineral resources themselves for various in situ applications.

Other Exploration Efforts

There are 18 previous missions that have returned data of the Martian Moons. Mariner 9 was the first to provide images, as well as insight into the topography and moons' orbits. The Viking missions (1&2) were able to capture significant coverage of the moons in the visual, inferred, and ultraviolet spectrum. These missions were also able to provide a terrain model and mass and density estimates. The Soviet mission Phobos 2 in 1989 was able to return radiometric, spectroscopy, magnetic and gamma ray data before it failed trying to land on Phobos. Most recently the Emirates Mars Mission claims the highest resolution images of the Deimos service.

A multi-national collaboration to explore the Martian moons is being led by JAXA and is called the Martian Moons Exploration (MMX) mission. MMX is scheduled to launch in 2024 (Kasakatsu, 2023). MMX inherits from the previous missions of OSIRIS-REx, Hayabusa, and Hayabusa2, all of which were asteroid sample return missions. MMX will also include a sample return specifically from Phobos. The mission differs from its predecessors in that it will include landing legs for surface operations and will deploy a small, wheeled rover on Phobos surface. The mission will also use multiple sampling techniques to collect the samples (approximately 10g). After leaving Phobos it will do Deimos flybys before returning the sample to Earth in 2029.

MMX instruments include:

- TElescopic Nadir imager for GeOmOrphology (TENGOO)
- Optical RadiOmeter composed of CHromatic Imagers (OROCHI)
- Light Detection and Ranging (LIDAR)
- MMX InfraRed Spectrometer (MIRS)
- Mars-moon Exploration with GAmma rays and NEutrons (MEGANE)
- Circum-Martian Dust Monitor (CMDM)
- Mass Spectrum Analyzer (MSA)

This document assumes the successful launch of MMX and that its major scientific products will be available before DREAM launches. The DREAM mission is proposed as a mission that is purposefully differentiated from MMX.

Low-Gravity Challenges

The authors believe that the engineering difficulties associated with mining in low gravity environments are significant, especially when the bodies are essentially cohesionless. In these environments, there is very little reaction force for interacting with the material. It is difficult to comprehend that an adult would weigh merely a couple grams on the Deimos surface and an object dropped from eye level would take approximately 19 seconds to hit the ground. This means even the smallest forces will cause material to fly away, creating dust clouds and other hazards for the spacecraft. The contact of OSIRIS-REx with the asteroid Bennu exemplifies these issues: as TAGSAM contacted the asteroid surface and the rockets pushed the spacecraft away from the asteroid, it is estimated that over a ton of material was ejected while only 250 grams of material was collected.

The utilization of any resources from the Martian moons is largely prevented by a lack of operational knowledge in the more practical considerations of landing and interacting with the surface and subsurface material in a low-gravity environment. DREAM will focus on practical problems of landing, anchoring, and interacting with surface material within the low-gravity surface environment.

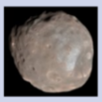
High-Level Mission Decisions

A major decision required for the mission was assessing which Martian moon was more interesting, viable, and accessible for DREAM. The major comparison metrics to compare Phobos and Deimos were:

- **Accessibility:** How much delta V is required to visit each body will influence the timing and allowable mass for interesting science instruments.
- **Orbital period:** A larger orbital period means simplified operations as comms to Earth or a satellite can happen for a longer stretch of time. Less autonomy may be required.
- **Maximum continuous lighting at hemispheres:** Similar to orbital period, longer continuous lighting simplifies mission design and operation as solar power can be used for longer stretches of time.
- **Potential for ISRU – mining:** Composition and quantity of each body is important to consider if they are to be used for mining.
- **Potential for ISRU – staging point for human Mars mission:** Using a Martian moon as a staging point means looking for locations that can be easily accessed and anchored to, and for locations that provide havens for radiation shielding.
- **Potential for ISRU – comms to Mars surface operations:** Similar to using the Martian moons as a staging point, communicating with a potential Martian surface base will add value to any future missions. The comparison criteria here are how much of the Martian surface is visible from each moon and how long the surface is visible for.
- **Body of knowledge:** Important to consider is the value of the data that the mission will provide. The MMX mission is planned to assess both Phobos and Deimos. However, a larger portion of the MMX data will be focused on Phobos.

Table 1 summarizes the comparison of Phobos and Deimos as targets for DREAM based on the described comparison metrics.

Table 1: Comparison of Phobos and Deimos as sole targets for a resource assessment mission.

Option	Accessibility (Required delta V)	Orbital period	Max continuous lighting duration in hemispheres	Potential for ISRU – mining	Potential for ISRU – staging point for human Mars mission	Potential for ISRU – comms to Mars surface operations	Body of knowledge
Phobos 	From Earth: 5.1-6.1 km/s From Mars: 4.6-5.1 km/s	7.5 hrs. Less stable temp and comms for potential surface operations	Northern: ~140 days Southern: ~95 days	Larger mass may mean higher probability of useful resources.	Large volume and mass may mean easier construction to support future missions. Stickley crater is a great candidate for radiation shielding.	% of Mars surface visible: 90.5% % time a Mars surface site is visible: 38%	Most data from MMX will focus on Phobos. Sample return will acquire sample at shallow depth, rover will traverse surface.
Deimos 	From Earth: 5.0-6.0 km/s From Mars: 4.5-4.9 km/s	30 hrs. More stable temp and comms for potential moon/surface operations	Northern: ~300 days Southern: ~225 days	Current data suggests composition is similar to Phobos	Smoother surface topography may mean easier construction but less potential for radiation shielding	% of Mars surface visible: 97.5% % time a Mars surface site is visible: 45%	MMX will acquire surface spectroscopic data only. Larger knowledge gap.

Given these criteria, DREAM is preferably targeted at Deimos and, due to cost, complexity, and delta-V constraints, DREAM will neglect studying Phobos and Mars.

Another major decision was whether to send a signal spacecraft or a small swarm. The evaluation criteria are mass, reliability, operations, complexity, and cost. These considerations are summarized in Table 2.

Table 2: Comparison of using a single satellite or a swarm for a resource assessment mission.

Option/Factor	**Single**	**Swarm**
Mass	Higher mass for all subsystems on one craft, more mass per impactor	Lower individual mass per spacecraft, lower sensor power
Reliability	Loss of spacecraft loses entire mission, lower	Distributed architecture mitigates risk of single failure, higher
Operations	Simple and well-known, mission design reusable	Distributed, requires inter-swarm communications and coordination
Complexity	Lower due to known components and mission structure	High and many unknown mission-relevant problems
Cost	Baseline to existing mars missions, normal	Possibly lower, but not at this stage in development

A third option has become more common in recent missions. Instead of having multiple small spacecraft with independent communications, navigation, and propulsion subsystems, several missions have utilized a single large spacecraft bus with many small sub deployments. This is best demonstrated by JAXA's Hyabusa2. Haybusa2 included 4 small rovers/sensor packages to explore the asteroid surface, a single shot small carry-on impactor, several deployable cameras, and a sample return capsule. These sub deployments allowed a single spacecraft to have multiple different functions while reducing the need for duplication of major spacecraft systems. DREAM will follow this architecture.

Internal Structure

Because the internal structure of Deimos is both currently unknown and unstudied by MMX, and because of its importance for utilization of large-scale space resources from the moon, there is a significant opportunity in the scientific exploration of this topic. Internal structure of planetary bodies has been studied with a variety of methods in the past. These methods can be divided into the two categories of remote sensing, including orbital of magnetitic fields and high energy particles, and in situ interaction with the body, using seismology and impactors. Because DREAM is already focused on in situ interaction with Deimos, the later methods are favored, and an impactor will be included in our mission design. The impactor can be used to eject material for spectral analysis and for an excitation source for seismological detections.

Summary

The high-level mission concept has been reduced to the following key elements:

- Single spacecraft with sub-deployments
- Mechanism for subsurface access (impactor)
- Science instruments
- Soft landing
- Anchoring mechanism technology demonstration
- No sample return

Mission Objectives

The overarching objective of the DREAM mission is to evaluate Deimos for in-situ resource utilization (ISRU). More specifically, the mission aims to assess the geology and composition of Deimos to determine what resources may be available for future extraction and utilization (Figure 3). Key sub-objectives include analyzing the ejecta plume from an implanted shaped charge to reveal subsurface composition and structure, performing a seismic survey to map internal structure and properties, demonstrating anchoring technology, and constraining microporosity and bulk continuity through seismic analysis.

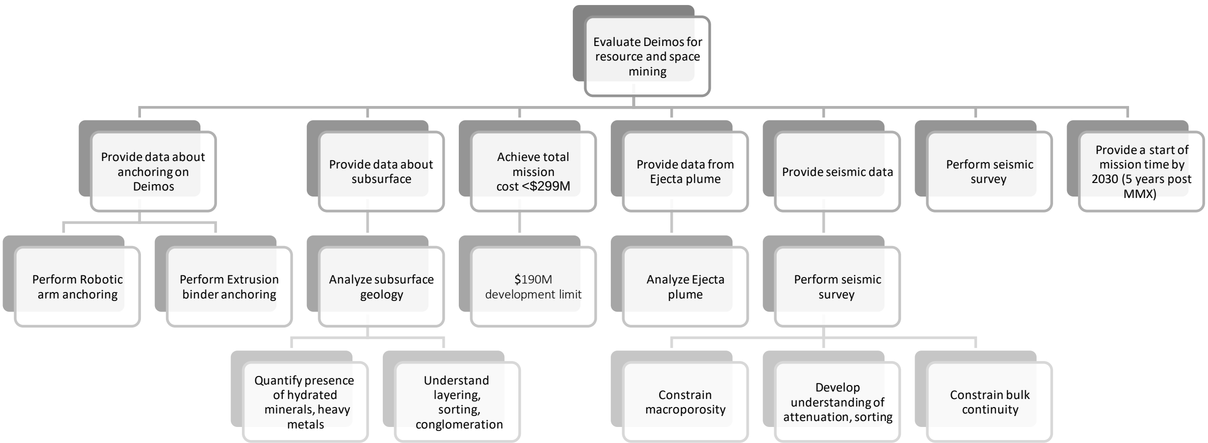


Figure 3: DREAM objective tree.

To break this down into more detailed goals, DREAM will detonate a shaped charge on the surface and observe the resulting ejecta plume with spectrometry instruments. Analysis of the plume will provide information on the subsurface composition and presence of valuable resources. Specifically analyzing for hydrated minerals as well as heavy metals.

It will also reveal physical properties like layering, sorting, and conglomeration. The mission will deliver and implant a shaped charge, deploy geophones, measure seismic activity from the detonation, and analyze ejecta. Constraining attenuation factors will inform models of Deimos' internal structure and porosity.

DREAM will also demonstrate and test two different anchoring methods. The spacecraft will use robotic arms with micro spine grippers to grab a boulder and test extruding binder onto the regolith to bind it together. Anchoring is critical to utilize Deimos for future ISRU activities. The mission will quantify the anchoring performance of these unconventional methods.

DREAM aims to assess the resource potential and engineering challenges associated with utilizing Deimos. Analyzing the subsurface, composition, internal structure and demonstrating anchoring technology will reveal the value of Deimos for future ISRU while advancing critical technologies needed to operate on small planetary bodies.

Mission Design

The chosen mission design is focused on delivering an existing sensor suite to Deimos and applying a newly developed shaped charge and grappling mechanism. A more detailed description of the DREAM mission design and key elements can be seen in Table 3.

Table 3: DREAM mission design breakdown.

Spacecraft Architecture	Payload Overview	Operations Concepts
Single spacecraft bus with deployable elements Reduced complexity, cost, and operation spectrum by using flight-proven design and sensors Leverages approaches used successfully on past missions like Hayabusa2	Spectrometry suite (visible, infrared, x-ray) Analyze surface and subsurface composition from orbit and in situ Laser altimeter and camera suite Ranging data for navigation, hazard avoidance, topographical maps High-resolution surface imaging in multiple bands Implanted shaped charge Active seismic source to induce waves for interior mapping Geophone array Record seismic waves for internal structure analysis Robotic arms and anchoring end effectors Grab a boulder with micro spine grippers Test regolith binder by extruding it onto the surface of Deimos	Launch and orbit stabilization Approach and achieve orbit around Deimos Map the surface with spectrometers to identify resources Implant shaped charge into the surface at a safe distance Identify landing site with a boulder for anchoring Descend and land on boulder, anchor using robotic arms Deploy geophone array onto the surface Detonate shaped charge and record seismic waves Test regolith binder sample as secondary anchoring method End of mission During the mission all data is sent back for analysis in bulk

This mission architecture concentrates proven instrumentation and new technology demonstrations into a focused concept that can reveal Deimos' resource potential and engineering challenges for future ISRU activities. It is unique in using a shaped charge to feed the geophones and an anchor mechanism based on robotic arms and regolith binder.

Anchoring

Anchoring Fundamentals

Almost all potential cases for using Deimos for ISRU require some method of "anchoring" to the body to allow the spacecraft to interact with the body. Due to the extremely low surface gravity, the term "landing" does not seem appropriate as even small reaction forces could decouple a spacecraft from the surface. "Docking" implies the mating of two engineered surfaces and does not fit as a good descriptor. Therefore, this report uses the term "anchoring" to describe the process of coupling a spacecraft to the surface of Deimos so that the spacecraft is stationary relative to the surface.

The low surface gravity (0.000306 g) and structure of Deimos makes anchoring a challenging problem. The measured high porosity of Deimos implies it is closer to a rubble pile consisting of loosely consolidated boulders and regolith. Interacting with the surface likely means interacting with discrete elements that are held together by very low forces. There is no single, obvious solution to the anchoring problem. On such a body, anchoring can be described as the process of holding on to enough mass to allow the spacecraft to react any required loads without significantly accelerating away from the surface. The free body diagram is shown in Figure 4, and includes the force of gravity on the spacecraft, the force of gravity on the pile of rocks and regolith the spacecraft is coupled to, and a reaction load.

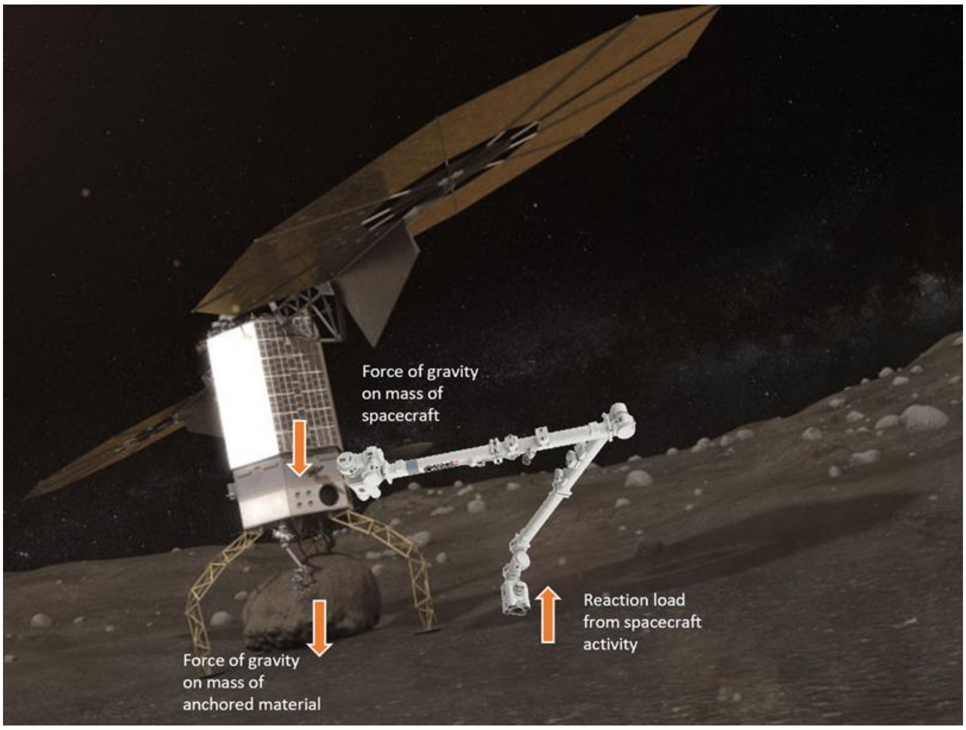


Figure 4: Simplified free body diagram showing the relevant forces on a spacecraft anchored to a body. Image adapted from Asteroid Redirect Mission (Gallagher et al. 2020).

The fundamental question that first needs to be answered is how much mass a spacecraft needs to anchor to. To do this, the spacecraft mass range is first estimated using examples of spacecraft masses from relevant missions: Hayabusa, MMX, Psyche, and OSIRIS-REx. The launch masses were used as that info was more readily available, though the actual spacecraft mass will vary once at the target body. For this mission, the spacecraft mass will be better estimated once more variables are known.

The required reaction load must also be estimated. Reaction loads involve interaction with the surface, and in future ISRU applications these may include actions such as scooping up regolith for beneficiation or drilling into rock to set up a base. Estimates for such actions on planetary bodies include 250 N for scooping (Zacny et al. 2006), 22 N for percussive scooping (Zacny et al. 2006), and 100 N for rotary percussive drilling (Zacny et al. 2009). One can now subtract the force of gravity of the spacecraft from the reaction load to estimate the required amount of mass to anchor to. Using the bulk density of Deimos, the mass can then be converted to an approximate volume of material that the spacecraft should anchor to.

Table 4 shows the results of such calculations. The spacecraft mass is shown to be negligible compared to the required anchoring mass. 100 N is baselines as the required load to react against to obtain a rough order of magnitude estimate. The conclusion from this exercise is that it does not take an unreasonable amount of volume to react a reasonable load. 23 m^3 corresponds to a sphere of approximately 1.7 meters in diameter, assuming a density equivalent to the bulk density of Deimos. A consolidated sphere may be significantly denser, and therefore lower in size to reach the same mass.

Table 4: Breakdown of calculations for first order estimate of the anchoring requirements of the spacecraft.

Parameter	**Spacecraft mass range**	**Loads to react**	**Required Anchored mass to react loads**	**Corresponding Deimos Volume (assuming bulk density)**
Value	530-4000 kg	100 N	33 metric tons	23 m^3
Note	Based on Hayabusa, MMX, Psyche, OSIRIS-REx launch mass	Scooping, drilling operations	Taking spacecraft mass to be negligible	Assumes bulk density of Deimos. Corresponds to sphere with diameter 1.7m
Source	(Beshore et al. 2015) (Tsuda et al. 2013) (Lord et al. 2015) (Miyamoto, 2016)	(Zacny et al. 2009)	calc	(Ernst et al. 2023)

It is not unreasonable to suggest that boulders of such size exist across the surface of Deimos. Figure 5 shows one of the highest resolutions images taken of Deimos by the Viking 2 Orbiter. Large protruding boulders “10-30 m across” are visible. Such boulders can be potential candidates for anchoring a spacecraft. However, there is always a risk that a sufficient boulder is not readily available near a target location.

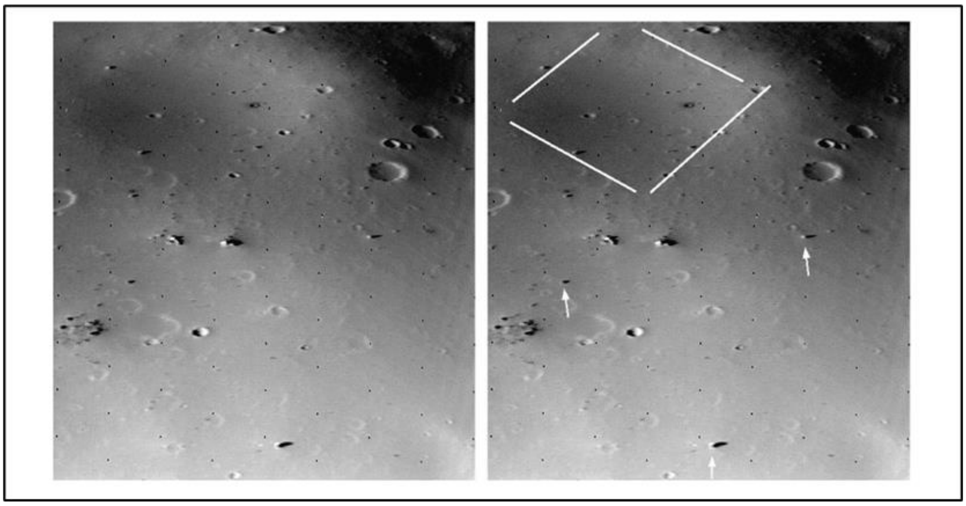


Figure 5: Surface of Deimos imaged by the Viking 2 Orbiter. The image covers an area of 1.2 km x 1.5 km. Left: Original image. Right: Same image with arrows pointing to boulders 10-30 meters across (Williams and Friedlander, 2015).

Literature Review

A literature review of anchoring concepts shows there has been extensive work tackling the challenge of coupling a spacecraft to a low gravity planetary body. In general, the concepts could be categorized into three groups of ideas: (1) concepts that involve some sort of burrowing or drilling into rock/regolith to anchor into the subsurface, (2) concepts that involve some sort of adhesion element to adhere to the surface of rock/regolith, and (3) concepts that wrap around an object to secure to it. These categories are described in Figure 6 with some examples from literature included as references.

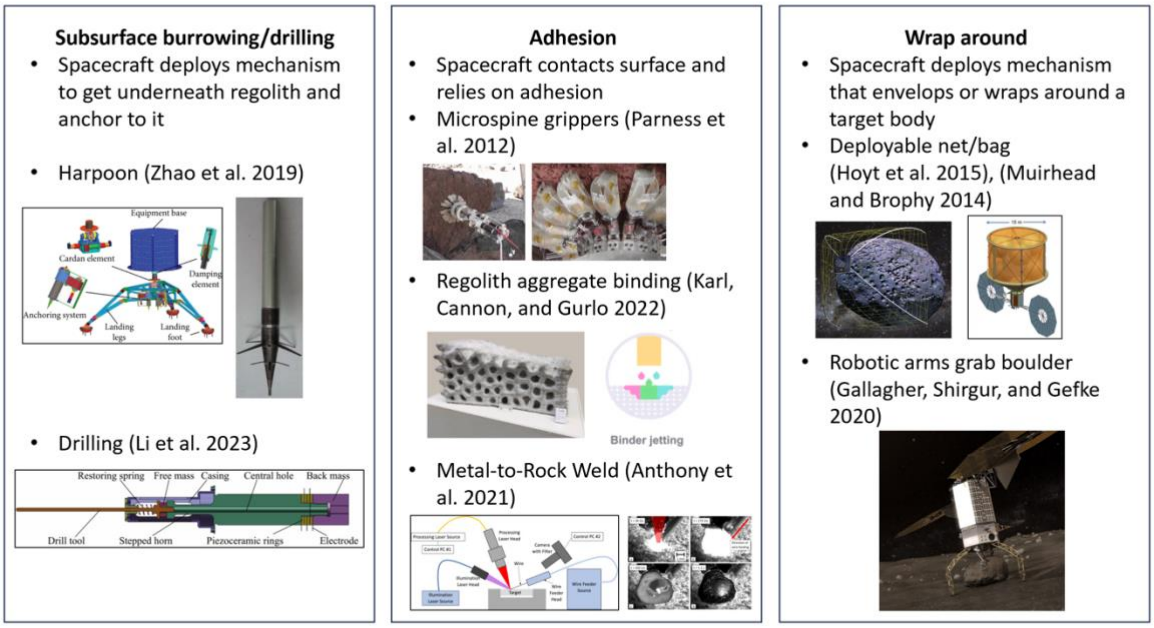


Figure 6: Anchoring concepts grouped into three categories: subsurface burrowing/drilling, adhesion, and wrap around. Images of example concepts from literature are added for reference.

Subsurface burrowing/drilling. The concepts in this category use some sort of mechanism to penetrate regolith or rock and anchor to it. This could be something like a harpoon with deployable fingers shown in Figure 7 (Zhao et al., 2019), or a drill (Li et al., 2023). While these mechanisms are light and compact, in loose regolith they would only interact with the unconsolidated material above the point that was burrowed or drilled into, meaning there is little mass above the mechanism to react load. These ideas may be more applicable to a planetary body with a significantly larger surface gravity than Deimos.

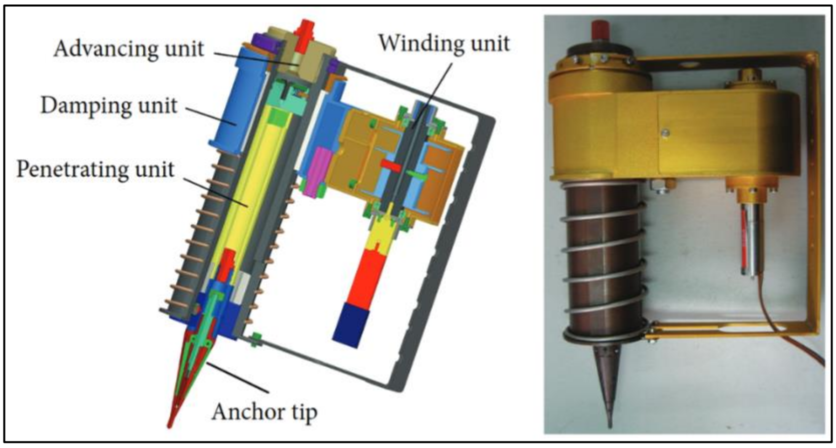


Figure 7: Diagram (left) and picture (right) of the anchoring system developed to be deployed on the legs of a spacecraft landing system (Zhao et al., 2019).

Adhesion. The concepts in this category use an adhesion element to bond to the surface of rocks or regolith. Metal to rock welding could adhere metal from a spacecraft to a rock or boulder on Deimos. Regolith aggregate binding involves the use of an engineered binder that is brought by the spacecraft to either glue elements of the spacecraft to the surface of Deimos or to bind regolith together into a large enough block to anchor to. This is not unlike terrestrial construction technology that uses aggregate binders such as spray-on “shotcrete” and rock bolts to construct strong supporting elements (Figure 8). Terrestrial spraying of concrete is an economic, fast, and flexible construction method, but cannot function in the extreme vacuum and temperature environment of space. Development of an equivalent technology could prove useful for future in-space construction projects.

Figure 8: Top: Dry spraying of shotcrete onto a construction site by a construction worker. Bottom: Wet spraying of shotcrete by a hose at the end of an actuated arm on to a surface with a metal lining (“Sika Sprayed Concrete Handbook by Sika AG - Issue” 2021).

Aggregate binding for space applications is an active area of research yet to be demonstrated on a mission. Figure 9 shows various concepts for regolith bonding grouped into several categories. While this chart was made for Martian regolith and Mars conditions in mind, it shows the variety and scope of the current research.

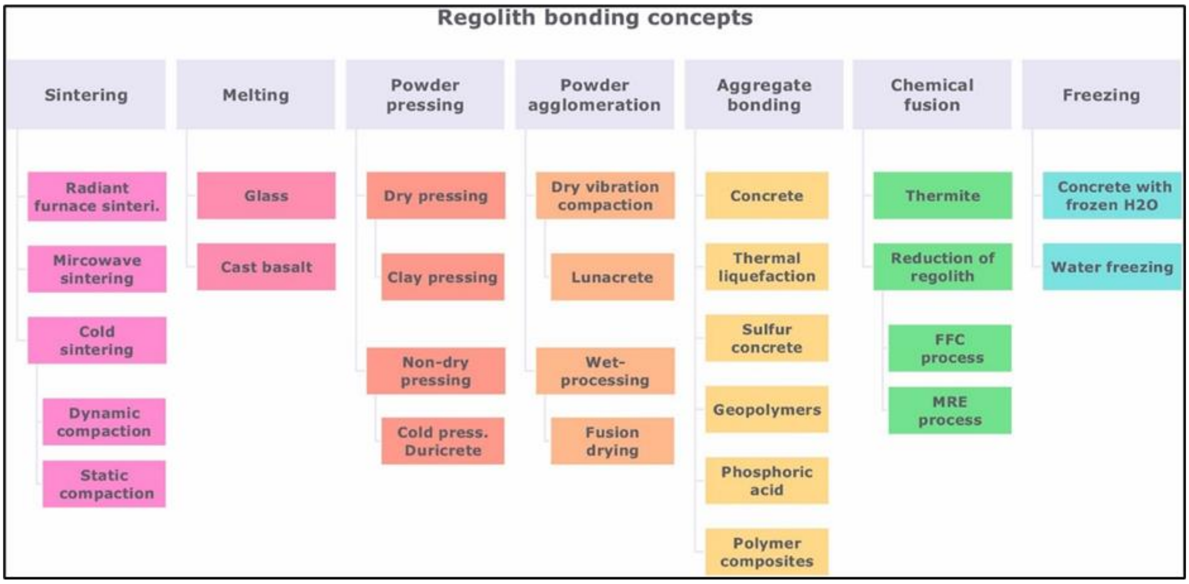


Figure 9: Proposed concepts for regolith bonding on planetary surfaces (Karl, Cannon, and Gurlo 2022).

Of these concepts, aggregate binding may be most applicable, as it may not require beneficiation or additional processing – the technology may be developed to simply apply the binder to the surface as is currently done with shotcrete on Earth.

Metal to rock welding is another approach investigated to adhere the metal of a spacecraft to a surface rock. The concept involves the use of a high-power laser to melt and bind a metal structure to a target rock (Figure 10).

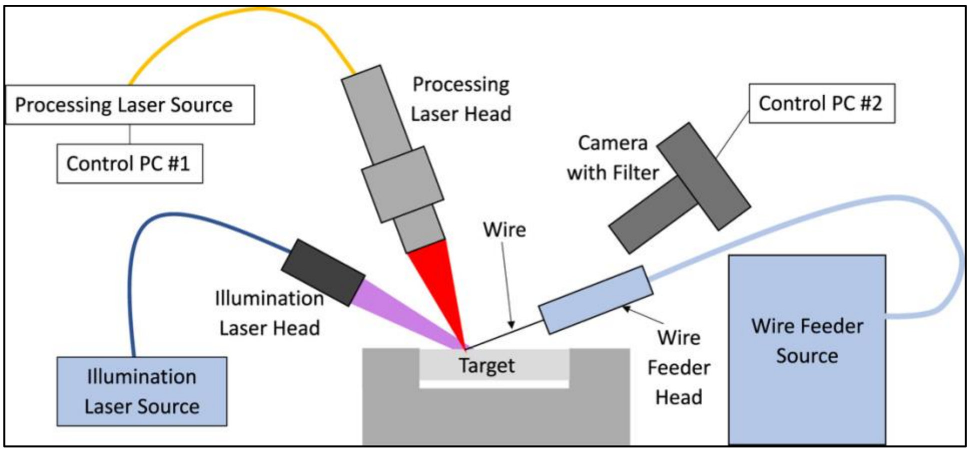


Figure 10: Diagram of the metal to rock welding test setup (Anthony et al. 2021).

Testing showed the concept was viable only in certain conditions. The resulting weld bead using a traditional wire feeder was brittle and not suitable to react useful loads. Using the laser to first drill a hole and use the hole as the weld volume yielded reaction forces up to 115 N (Anthony et al. 2021). The approach also comes with additional risk, as the target rock must be both massive enough to anchor to and a suitable composition to weld to.

Perhaps the most tested of all adhesion concepts are microspine grippers, shown in Figure 11.

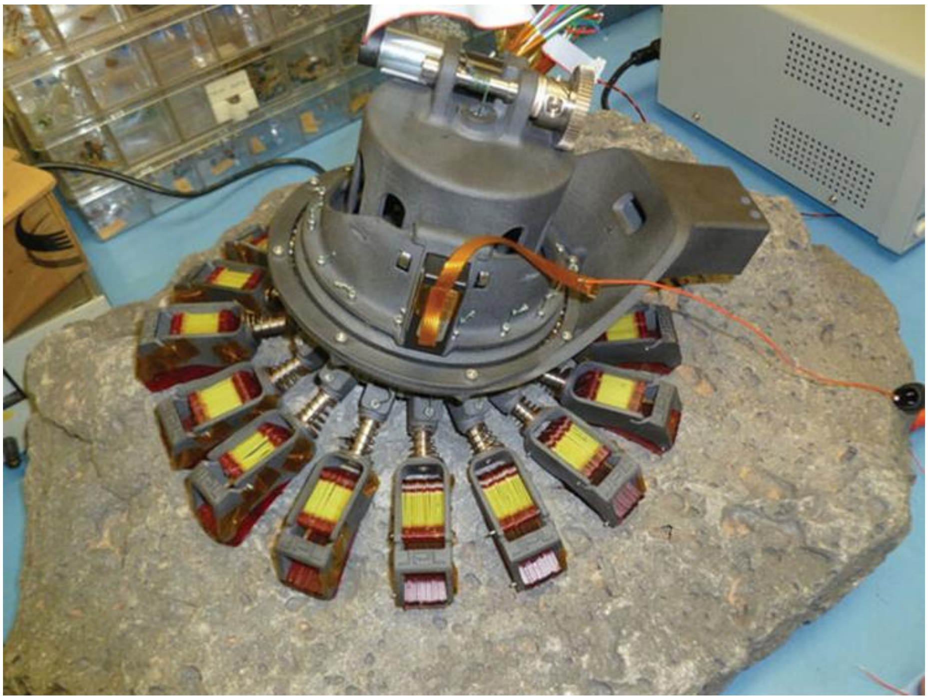


Figure 11: Testing of the microspine gripper design on a natural rock (Parness et al., 2013).

Microspine grippers use a large quantity of actuated, individual, small hooks or spines that preload onto the surface of a rock. This technology was baselined for the NASA-proposed Asteroid Redirect Mission concept. Significant development and testing of this concept has been done at NASA JPL, demonstrating that this technology can hold significant enough preload for rock coring or simply anchoring to a surface. Table 5 shows test data using this approach on a variety of simulants. That data shows the importance of finding a consolidated boulder to anchor to, such as vesicular basalt which can provide a reaction load on the order of what might be expected for mission operations (100+ N).

Table 5: Test data of microspine gripper design reaction loads in different axes on various rocky simulants. Taken from Parness et al., 2013.

Material	Normal (N)	45° (N)	Tangent (N)
Bonded pumice	2.2	1.0	45.4
Loose lava rock	2.7	0.3	0.5
Pea pebbles	3.1	1.1	0.4
Sand	0.3	0.2	0.7
Saddleback basalt	32.3	54.5	44.1
Bishop tuff	120.5	91.8	110.7
Vesicular basalt	189.5	113.2	281.4
Volcanic breccia	132.6	83.2	164.1

Wrap around. The concepts in this category involve the use of deployable mechanism wraps around a target. The deployable mechanism can be as large as a net or bag that completely envelops the body. For a body as large as Deimos, such a mechanism would not be feasible. Instead, a mechanism can wrap around a smaller volume body such as a boulder. This concept was combined with the microspine gripper approach for the NASA-proposed Asteroid Redirect Mission. Robotic arms would maneuver around a boulder and actuate the grippers to grab onto it (Figure 12). However, the purpose of this was to take off from the surface of the asteroid with the boulder secured. Legs would then wrap around the boulder to further secure it.

Figure 12: Artist rendering of the Asteroid Redirect Mission spacecraft grabbing a boulder from the surface of an asteroid (Gates 2016).

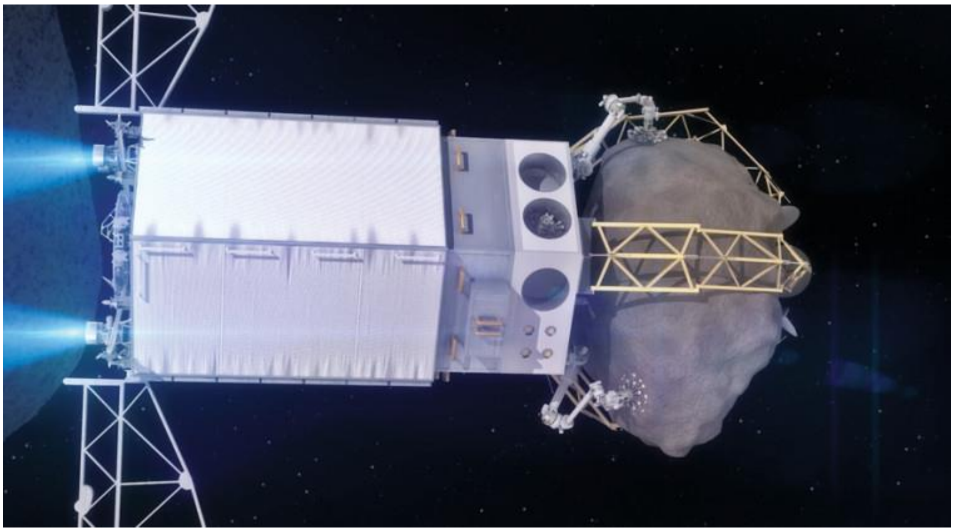


Figure 13: Artist rendering of the Asteroid Redirect Mission spacecraft with legs wrapped around the volume of a captured boulder (Gates 2016).

Chosen Anchoring Concepts and Notional Con Ops

Literature review shows many of these anchoring concepts are not viable for a body like Deimos and come with high risk or a significant amount of development and testing. For DREAM, the concept that is most viable and lowest risk is the general approach already baselined by NASA for the Asteroid Redirect Mission: using robotic arms and microspine grippers to anchor to a boulder on the surface. Microspine gripper design has undergone significant testing at NASA Jet Propulsion Laboratory and have been shown to react significant loads. The risk of this method is the requirement to locate a suitable landing site with a boulder. However, imaging from the Viking 2 Orbiter (Figure 5) shows that it is reasonable to expect a selection of large boulders on the surface.

DREAM will also incorporate a test of an alternate, experimental anchoring approach that will complement the micrograppers. Regolith aggregate binding is chosen as the secondary anchoring approach that would be developed and ultimately tested in space by the mission. The additional approach of a regolith aggregate binder can empower anchoring to low gravity rubble pile bodies without the presence of a high-mass boulder. Anchoring would not be limited to locations with large, consolidated, and accessible structures. Loose regolith and rocks can be bound together to form a consolidated mass for anchoring or other construction purposes like shelters. For DREAM, this approach is considered a high-risk tech demo and is not mission critical.

Figure 14 shows a simplified anchoring concept relevant to operations for DREAM.

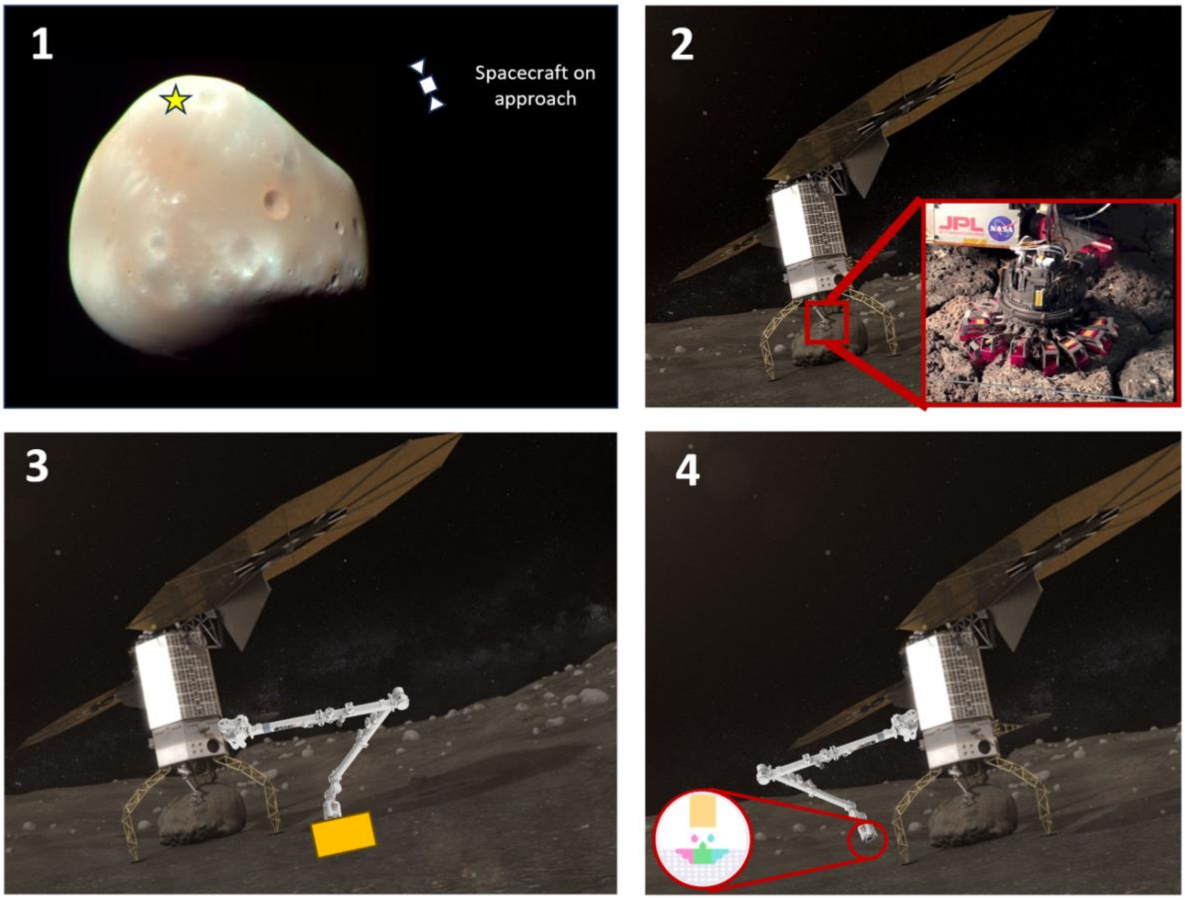


Figure 14: Simplified Con Ops of anchoring operations for DREAM. 1: Evaluate landing site. 2: Robotic arms and microspine grippers anchor to target boulder. 3: Robotic arm preloads seismometer for seismic test. 4: Robotic arm tests regolith aggregate binding.

On approach to Deimos, the spacecraft scouts and identifies target boulders for landing and target areas for seismic testing. After emplacing the shaped charge, the spacecraft maneuvers towards the target boulder and actuates 2 robotics arms with microgrippers and grabs onto it. Once stable, a third robotic arm carefully places a seismometer against the surface. A force torque sensor on the robotic arm measures reaction loads and torques, and an accelerometer on the spacecraft body checks for movement. This acts as the first real test of the anchoring system, as the robotic arm will increase preload on the seismometer until the spacecraft senses significant motion. The spacecraft then orients the onboard science instruments towards the direction of the shaped charge. This requires one or two degrees of freedom on the spacecraft to ensure the instruments can observe the plume from the shaped charge. After the shaped charge and seismometer experiment, the robotic arm then releases the seismometer and maneuvers to a different location on the surface to begin the aggregate binding tech demo. Binder is heated and extruded onto the regolith. Once the binder is extruded and solidified, the robotic arm will then interact with it and measure reaction loads using the same torque force sensor. This interaction can include pushing on the bound aggregate to check for fracture strength and pushing it away to estimate total bound mass. The returned force data and imagery will inform the success of this specific aggregate binder approach for construction and anchoring on the surface of Deimos. Near the end of mission life, the robotic arm and/or any thruster will test the reaction forces of the microgrippers by pushing the spacecraft away from the surface. The resulting inertial data will inform the success of the microgripper approach to anchoring.

Instrumentation

Given the scientific objectives of this mission, the instrument selection will need to be carefully decided to select the appropriate instruments to achieve mission goals. These instruments will be involved in completing numerous mission operations, including navigation, site selection, analysis of the eject plume, mapping of the moon's surface, obtaining high-res images, and more. While there are various instruments that have been used for a variety of purposes in the space industry, it is important to select instruments that will not only achieve the mission objectives, but to use instruments that can be used in multiple operations. This will allow for less volume and weight to be allocated towards instrumentation and can decrease mission cost. In order to make sure the correct instruments were selected for this mission, a review of instruments, as well as past missions with common operations, was conducted.

OSIRIS-REx

The first mission that was studied was OSIRIS-REx, which traveled to the asteroid Bennu with the objectives of mapping and analyzing the surface, as well as a sample return. This mission used nine instrument suits, five of which were science based, two for sample collection and return, and another two for navigation ("OSIRIS-REx Mission" n.d.). Because DREAM will not include a sample return objective, the sample return instruments are neglected.

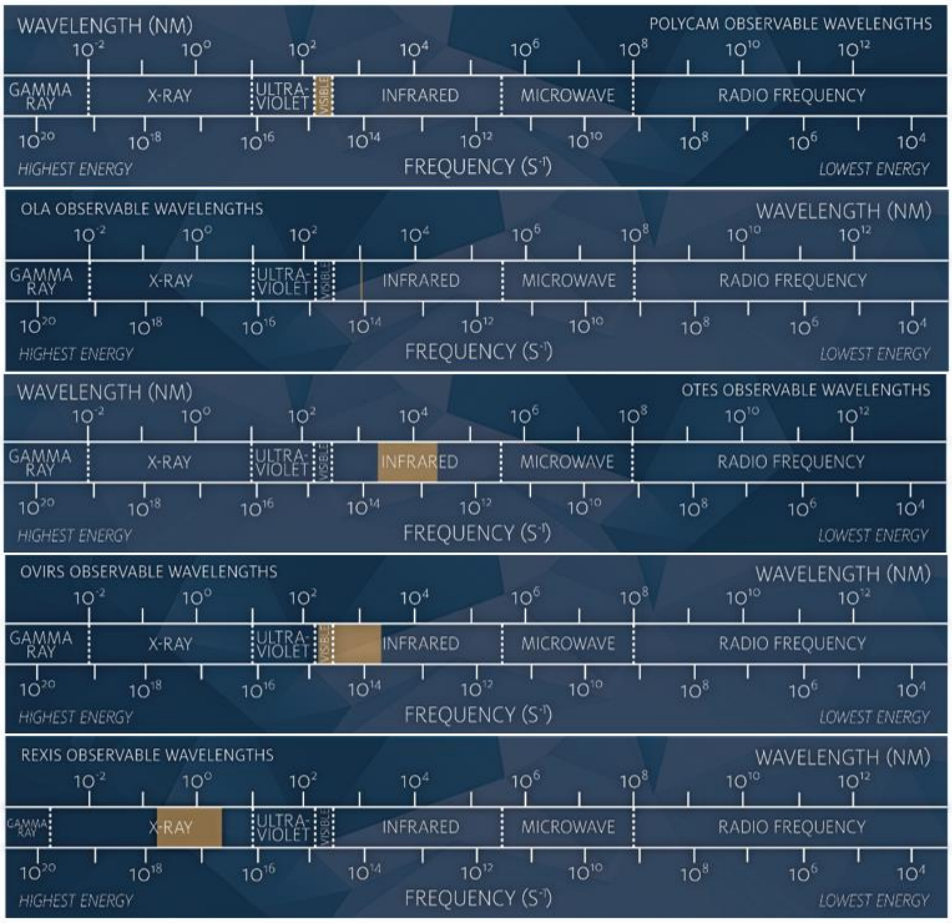


Figure 15: This image shows the spectral range for each of the science-based instruments on OSIRIS-REx. Note that the top spectral range for PolyCam is identical to the other cameras in the OCAMS suite (OSIRIS-REx Mission" n.d.).

The science-based instruments were OCAMS, OLA, OTES, OVIRS, and REXIS. Figure 15 shows the spectral range for each of these instruments. This shows that a large range of the spectrum is covered, which allows for a variety of data to be collected. OCAMS (OSIRIS-Rex Camera Suite) consisted of three cameras that provided global image mapping of the asteroid's surface and recorded the sampling event: PolyCam, MapCam, and SamCam. PolyCam was a long-range telescope that located the asteroid from a distance, identified hazards, and obtained high-resolution images of the surface at short range. MapCam was a medium range camera that mapped the asteroid in color, provided images used for topographic maps, and searched for satellites and gas plumes around the asteroid. The imaging could occur in panchromatic (clear) and wide-band spectral in the blue, green, red, and near-infrared. SamCam was a close-range camera that observed the sampling process and imaged the mechanism after sampling.

OLA (OSIRIS-Rex Laser Altimeter) was a scanning LIDAR (light detection and ranging) that measured the distance between the spacecraft and the surface of Bennu, allowing for high-resolution topographical information. This instrument also supported other instruments and the data supported navigation and gravity analyses. OTES (OSIRIS-Rex Thermal Emission Spectrometer) provided mineral and temperature information about the surface of Bennu, which allows for surface mineral composition to be acquired, as well as information on the surface's physical properties. The data from this instrument allowed for mineral composition and temperature distribution maps to be created, as well as aided in picking candidate sample sites. OVIRS (OSIRIS-Rex Visible and Infrared Spectrometer) measured visible and infrared light, providing spectral maps that show mineral identity and organic matter globally. The spectral information also aided in candidate site selection. Finally, REXIS (Regolith X-ray Imaging Spectrometer) determined present elements and their abundance at the surface of Bennu through a telescope that imaged the X-ray fluorescence line emission. Figure 16 depicts the locations of all the science instruments in correlation to one another.

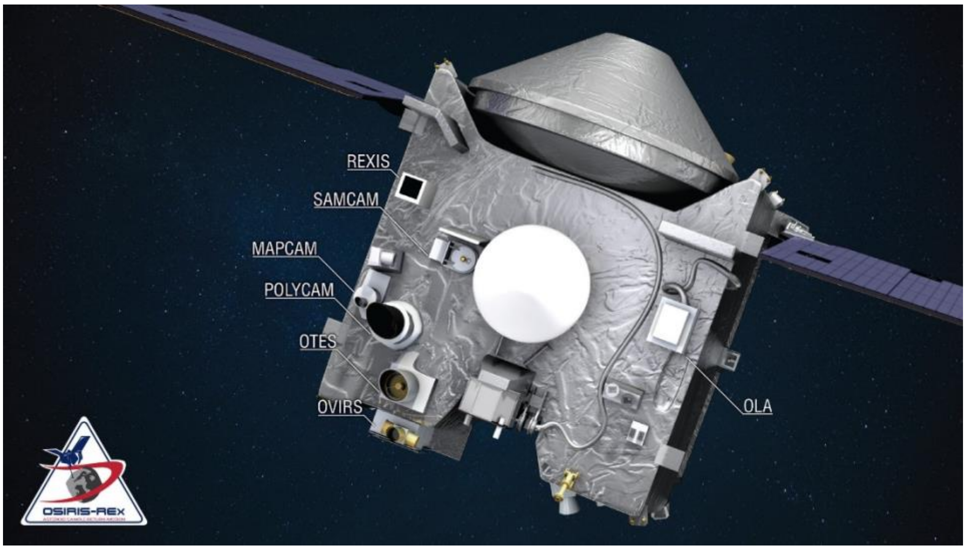


Figure 16: This image shows a depiction of the OSIRIS-REx spacecraft and where each of the science-based instruments are located on it (Photo from NASA's OSIRIS-REx Twitter post).

The navigation-based instruments were GN&C LIDAR and TAGCAMS. GN&C (redundant guidance, navigation, and control) LIDAR provided the spacecraft with information regarding range to the surface during sample collection to ensure the spacecraft remains safe during the process. TAGCAMS (Touch-and-Go Camera System) aided in guidance, navigation, and control of the spacecraft. It contained two cameras called NavCams and StowCam. NavCams was used for optical navigation through imaging track star-fields and landmarks on Bennu to determine the spacecraft's position during operation and contained two monochrome cameras capable of acquiring still images and high-definition video. StowCam was used to verify proper storage of the sample and was a color camera capable of still images and high-definition video.

LCROSS

The next mission that was studied was LCROSS, a mission launched with LRO that aimed to determine if water-ice is present in a permanently shadowed crater on the Moon's south pole. This was achieved by sending an impactor into the crater, causing a plume to form, and exposing material that was not likely to have been in direct sunlight for billions of years ("LCROSS" n.d.). Six instrument types were included in this mission with some redundancies: a visible camera, two near infrared cameras, two mid infrared cameras, a visible spectrometer, two near infrared spectrometers, and a total luminescence photometer. Figure 17 shows these instruments on the payload panel of LCROSS.

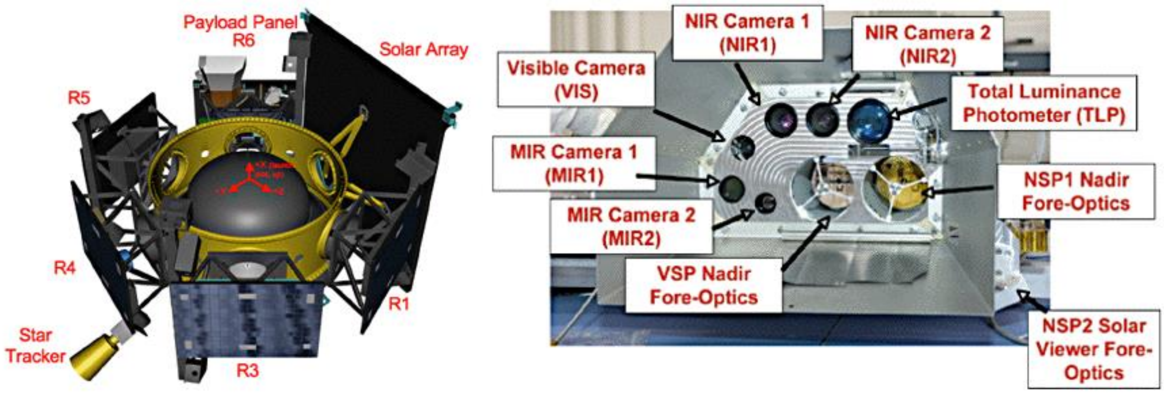


Figure 17: This image shows a diagram of LCROSS (left) and the layout of the instruments on panel R6 (right). All nine instruments are shown (Photo from NASA Master Catalog ID: 2009-031B).

A Centaur upper stage was used for the impactor and was initially attached to LCROSS. LRO and the Centaur-LCROSS satellite were all launched to the Moon together. Once reaching a parking orbit, LRO separated from the Centaur-LCROSS satellite, which continued to a separate orbit. Eventually, the Centaur separated from LCROSS and crashed into Cabeus crater in the south pole, creating a debris plume. A shepherding spacecraft (SSC) was also attached to the Centaur impactor and guided it into the trajectory towards the crater ("Lunar Crater Observation and Sensing Satellite (LCROSS)," n.d). The SSC separated from the Centaur impactor before impact and followed behind with the purpose of collecting images and other data on the impact and ejecta. The SSC flew through the plume for approximately four minutes before it impacted into the surface. Four minutes after the Centaur impact, LCROSS flew through the resulting plume as well and collected data before LCROSS itself crashed into the Moon. This is where LRO comes back in as LRO's DLRE (diviner lunar radiometer experiment) was able to get infrared observations on the LCROSS impact as LRO flew past the impact site 90 seconds after contact.

MMX

As discussed above, MMX is a more recent mission that will focus on the Martian moons and is anticipated to launch in 2024. The main goals of MMX are to determine the origin of Phobos and Deimos, explore the early solar system volatile delivery across the snow line, and explore the evolutionary processes of the Martian surface and moons. While both moons are being visited and observed, there is a heavy focus on Phobos. The team working on MMX has created mission requirements that correspond to a mission objective each. While there are 10 mission requirements with varying focuses, only a single requirement has a focus on Deimos. The team would like to 'constrain Deimos' origin' and talk about spectroscopically observing a few areas of the moon, along with a study on the south pole basin in order to determine an estimate of the body's volume and density (Kuramoto et al. 2022). However, they also talk about obtaining these values for geological comparison of Deimos with Phobos. While it would be significant to learn more about the origin of the Martian moons and get more data on Deimos, DREAM aims to focus solely on Deimos with data collection in the way that MMX focuses on Phobos. This will equal out the disparity in amount of information on each moon as the amount of data that will be retrieved from the operations on and around Phobos will greatly outnumber the data that will be retrieved from a flyby of Deimos.

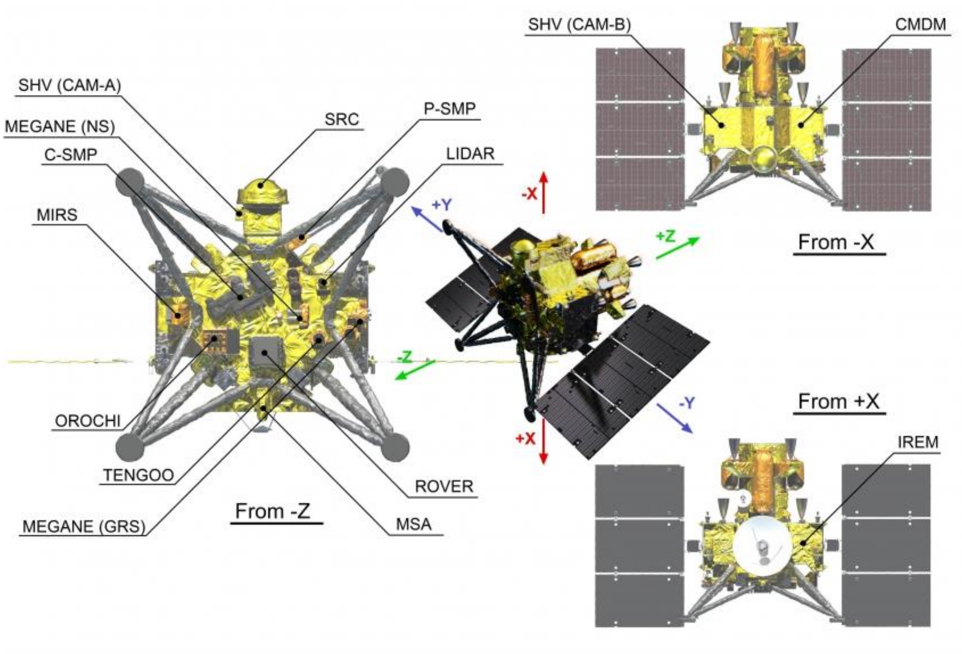


Figure 18: This diagram depicts the MMX spacecraft from various angles while showing the scientific instruments and more (Photo by JAXA Digital Archives).

MMX has six instruments included as part of the spacecraft, as well as a rover that has 4 instruments of its own. Figure 18 shows where the scientific instruments and other components are located on the spacecraft. The first instrument included is a laser altimeter. Next, there are two cameras onboard: a telescopic imager (TENGOO) and a wide-angle multiband camera (OROCHI) ranging from visible to near-infrared. Finally, there are three spectrometers: a near-infrared spectrometer (MIRS), an ion mass spectrometer (MSA), and a gamma-ray and neutron spectrometer (MEGANE). Additionally, the rover that will explore the surface of Phobos contains a laser raman spectrometer, a thermal radiometer, a navigation camera, and wheel cameras. A dust counter can also be found on the main spacecraft.

DREAM

From the review on previous missions and their instruments, it is clear that a few of these instruments are standard for exploratory missions, a few of the instruments are used in operations that are similar to operations planned for this Deimos mission, and certain instruments differ in operation but can be adapted to suit the needs of this mission. Table 6 summarizes the instruments discussed above, as well as their purpose and what mission they were involved in.

Looking at the common instruments of these three missions, a mix of cameras and spectrometers can be seen in every mission. Certain elements can be taken from each mission that aligns with the mission objectives of DREAM. Numerous instruments from OSIRIS-REx would be useful for this mission. Additionally, where there are navigation components for the sampling process, these can instead be used during the anchoring process as there will still be an approach to the surface. A set of instruments can also be taken from LCROSS as both LCROSS and DREAM focus on an impact event and analysis of the subsequent ejecta plume. The only difference here is that the main spacecraft will not be sacrificed later for another impact. Lastly, various instruments from MMX can be used for DREAM as the objectives are similar with the main differences being the target body and replacing sampling for anchoring.

Table 6: Summary of instruments and their purposes from OSIRIS-REx, LCROSS, and MMX.

Instrument	Purpose	Spacecraft
Visible Camera	Measures visible light to track locations, shapes, obtain high-res images, and more	OSIRIS-REx (OCAMS, TAGCAMS), LCROSS, MMX (TENGOO, OROCHI)
Near Infrared Camera	Measures near-infrared light to determine amount and distribution of water	LCROSS, MMX (OROCHI)
Mid Infrared Camera	Measures mid infrared light to determine amount and distribution of water, as well as the heat signal from the impact crater	LCROSS
Laster Altimeter	Measures light reflection emitted from a laser to obtain distances and provides data for topographic maps	OSIRIS-REx (OLA, GN&C), MMX
Visible Spectrometer	Examines emitted or absorbed light (in the visible/ultraviolet spectrum) of material to identify composition	OSIRIS-REx (OVIRS), LCROSS
Infrared Spectrometer	Examines emitted or absorbed light (in the infrared/near-infrared spectrum) of material to identify composition	OSIRIS-REx (OTES, OVIRS), LCROSS, MMX (MIRS)
Ion Mass Spectrometer	Measures velocity distribution function and mass/charge distributions to determine surface composition, search for gas torus, and escaping Martian atmosphere	MMX (MSA)
Gamma-ray and Neutron Spectrometer	Measures how gamma-rays change when interacting with materials and how neutrons escape materials to determine surface composition	MMX (MEGANE)
Regolith X-ray Imaging Spectrometer	Measures x-rays that were absorbed by the surface from solar wind/x-rays and then re-emitted to determine element presence and abundance	OSIRIS-REx (REXIS)
Total Luminescence Photometer	Measures total impact flash luminance and magnitude to give information on the initial energy of the impact	LCROSS

The first instrument that was selected is a laser altimeter, or LIDAR. Navigation is imperative to an exploration mission as there can be hazards that need to be navigated and it can be critical that the spacecraft stays within a certain orbit or height from the surface, depending on the target body. Additionally, there will be a redundant navigation system that will focus on the spacecraft descending to the surface during anchoring. It will be important to make sure that the descent is controlled, and the spacecraft does not crash into the boulder that will be the anchor. The robotic arm that lowers the seismometer to Deimos' surface and performs the regolith aggregate binding test will also need to be navigated carefully, otherwise equipment could end up impaired or nonfunctional.

Next, the spacecraft will need various cameras for navigation and data collection. A total of five cameras were chosen. A suite of cameras called DCS (DREAM Camera Suite) will consist of three cameras: a long-range telescope for navigation and high-resolution images of the surface at a short range, a medium-range camera for mapping topography and maps in color, and a wide-angle multiband camera that can capture data ranging from visible up to near-infrared light. This suite of cameras will be aimed towards the surface of Deimos. However, as the spacecraft anchors to the boulder, these cameras will be aimed towards the impact site so that the cameras can collect data from the ejecta plume. There will also be two other cameras in addition to the suite: a close-range camera that will observe the anchoring process and the aggregate binding test, and a navigation camera used for optical navigation through imaging track star-fields and surface landmarks. Both cameras will be capable of still images and high-definition video. The close-range camera will be pointed down towards the anchoring gear.

The last set of instruments to look at are spectrometers, which will be significant to DREAM since a mission objective is learning more about the geology and composition of Deimos. The first two spectrometers will be the visible and infrared spectrometers. They will allow material composition to be identified by using emitted and absorbed light in the visible/ultraviolet and infrared/near-infrared ranges respectively. The final instrument will be the x-ray imaging spectrometer. While the other types of spectrometers were good options, they would also find surface composition, which will be determined through the visible and infrared spectrometers. The x-ray imaging spectrometer allows for element presence and abundance to be identified. These three spectrometers will allow for valuable data on the geology of both the surface of Deimos, as well as the subsurface through observation of the ejecta plume.

Table 7: Instrument selection for DREAM. Instruments are in order from first discussed to last.

Instruments	How Instrument will be Utilized
DLA (DREAM Laser Altimeter)	Navigation upon approach and around Deimos, surface mapping, impact and anchor site selection, navigation to anchoring site and surface
ANC (Anchoring Navigation and Control)	Navigation of the spacecraft during decent towards the surface and during the anchoring process, navigation of the robotic arm to the surface for the seismometer and aggregate binding test
DCS-LRT (Long-Range Telescope)	Locate Deimos from a distance, identify hazards, obtain high-res images of the surface, impact and anchor site selection, check that the ejecta plume will be in partial or full visible light
DCS-MRC (Medium-Range Camera)	Map the moon's surface in color, provide images for topographical maps, search for other defining characteristics or points of interest
DCS-WAMC (Wide-Angle Multiband Camera)	Obtain images over the visible and near-infrared spectrum
CRC (Close-Range Camera)	Observe the anchoring process and aggregate binding test, obtain colored still images and high-definition video
NavCam (navigation camera)	Navigate the spacecraft through optics and determine the spacecraft's location during operation, obtain still images and high-definition video
DVS (DREAM Visible Spectrometer)	Collect mineral composition and organic matter data globally, impact and anchor site selection, baseline observations of impact site before impact, gather data from ejecta plume
DIS (DREAM Infrared Spectrometer)	Collect mineral composition and temperature data globally, provides information on surface properties such as particle size, impact and anchor site selection, baseline observations of impact site before impact, gather data from ejecta plume
DXIS (DREAM X-ray Imaging Spectrometer)	Collect element presence and abundance data globally, baseline observation of impact site before impact, gather data from ejecta plume

In total, 10 instruments were selected for DREAM, consisting of two laser altimeters, five cameras, and three spectrometers. Table 7 summarizes these instruments and how they will be used for DREAM. These instruments support mission objectives and operations by aiding in navigation, site selection for both anchoring and the impact, producing images and videos, and collecting data on topography, mineral composition, organic matter, temperature, element presence/abundance, and more.

Seismology

Seismology is a highly promising non-invasive approach for examining the internal structure of small planetary bodies, such as Deimos. Given the rocky composition, potential water-ice presence, and high electrical conductivities characteristic of these objects, seismic experiments provide exceptional depth penetration when compared against conventional electromagnetic techniques like ground-penetrating radar. Seismic exploration enables a more thorough understanding of the target's mechanical structure and composition, which is fundamental information needed to identify potential resources for in-situ utilization (Bernauer). This approach is particularly significant for Deimos, whose origin and formation remain subjects of debate. Understanding whether its composition aligns more closely with that of a captured asteroid or a traditional moon could yield critical insights into the history and evolution of the Martian system and the resources available. Furthermore, seismic data could reveal the presence of differentiated layers within Deimos, or conversely, support the theory of a more homogeneous, rubble-pile-like composition. Such knowledge is not only essential for academic curiosity but also holds practical implications for future exploration missions, potentially informing landing strategies, resource utilization, and the viability of sustained human presence. Thus, seismology emerges as an exploration technique of particular importance.

However, seismic exploration is not possible in all environments. Because this method relies on the propagation of acoustoelastic waves (seismic waves), particular material interactions and the lack of atmosphere could attenuate energy before it might be recorded by receivers. This is of particular concern for small planetary bodies like Deimos whose estimated porosity of more than 25% could result in detrimental attenuation. Table 8 provides a comparison of the seismic properties of the Earth's upper crust, the Moon, and Deimos. Although Deimos' potentially higher porosity might call into question the global propagation of acoustoelastic waves, no previous mission has studied seismicity on a small planetary body. Without a dedicated seismic exploration mission, it is not possible to draw this conclusion. Moreover, a lack of any seismic response would serve as a validation of the estimated porosity and may provide further insight into the dominant grain interactions of Deimos.

Table 8: Characteristics of seismic wave propagation for a 10 Hz source travelling in three different media. The seismic response of Deimos is almost entirely unconstrained.

	Porosity	Q-factor	Attenuation (Np/m)	Global Propagation
Moon	12%	<< 2400	0.0131	YES
Deimos	23-44%	UKNOWN	UNKNOWN	UNKNOWN
Earth Upper Crust	< 10%	> 4000	0.0078	YES
Source	(Murchie et. al.) (Xiao)	(Gillet et. al) (Nakamura et. al.)		(Nakamura et. al.)

Seismic experiments are comprised of two main components: sources and receivers. Sources are needed to create seismic waves that propagate through the subsurface. In conventional terrestrial exploration, active sources may consist of vibrators, explosives, or impactors. Naturally occurring passive sources may also be opportunistically harnessed to recover the same information if sufficiently strong and numerous. The energy created by these sources interact with the subsurface as they propagate through it, thereby encoding information about the material through which they traverse. When reflected back to the surface, an array of receivers can record their arrival time and strength. Although it is possible Deimos has sufficient natural seismicity to conduct a passive seismic survey, we propose the use of a shaped charge as an active energetic source (Bahia). Reaccreting debris from the initial impact will also serve as a secondary source with which further analyses can be done.

Shaped charges are a type of percussive charge specifically designed to focus the energy of the explosion in a desired direction (Figure 19). This is achieved through a unique geometric design of the charge's casing and the placement of an internal metallic liner. By actively directing the energy of the explosion, we not only reduce the risk of harmful debris being ejected towards our spacecraft, but we also minimize energy loss to vacuum. In other words, we maximize the amount of energy being spent to create seismic waves in the subsurface. A shaped charge also enables the option for an implant first, detonate later strategy during reconnaissance of Deimos. This would provide the spacecraft time to reach a secure landing site before the detonation ejected potentially harmful debris. This strategy was selected as an optimal risk reduction method.

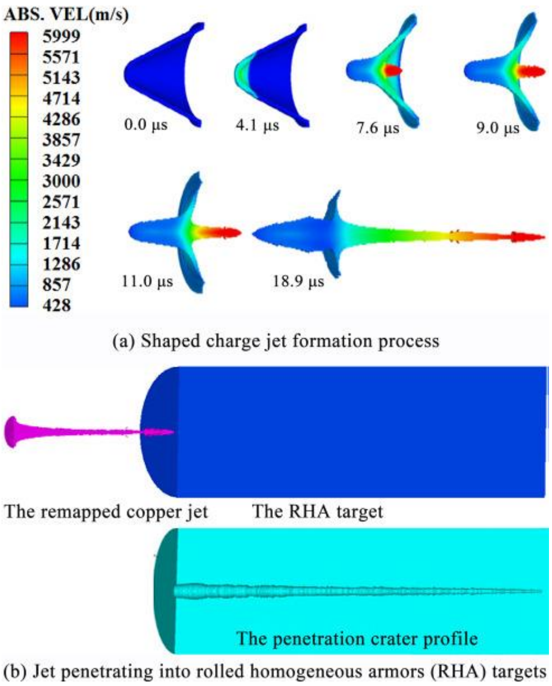


Figure 19: Formation of a shaped charge. (a) the jet created by the shaped charge cone. (b) the resulting impact profile in a sample material (Zhang et. al.).

After the shaped charge is implanted, the spacecraft will proceed to the selected landing site. From this point onward, acquisition of seismic data is relatively straightforward. The geophone array will be deployed to the surface using the spacecraft's robotic arm. Table 9 estimates the properties of this array based on the Martian InSight seismometer, SEIS. Once ready, the shaped charge can then be detonated. After listening for the initial burst of energy from the active source, the array will continue to operate with the expectation that reaccreting material may cause secondary microquakes. Because power and communications are shared with the main spacecraft, the operation of the geophones can continue indefinitely.

Table 9: Characteristics of seismic wave propagation for a 10 Hz source travelling in three different media. The seismic response of Deimos is largely unconstrained (Lognonné).

Volume	Weight	Power	Data rate
3 L	8.5 kg	<10 W	>15 Mbit/day

Risk

Risk has been registered and mitigated during the overall timeline and will be used to find and mitigate critical dangers to the project (Table 10).

Table 10: Risk register for DREAM.

RISK	Description	Severity * Probability	Mitigation Strategy
[1] Shape charge failure	Shaped charge fails to detonate and does not create the necessary impact force.	4*3= 12	kinetic due to impact, shaped share release speed = impact speed.
[2] Significant seismic attenuation	Seismic waves are attenuated by demos, due to its composition.	1*5= 5	Not necessary
[3] Ejecta instrument suite failure	The sensory equipment to detect and follow the ejecta does not work as intended. Decreased sensor output.	5*2= 10	Redundancy in instruments, substituted by other instruments.
[4] Uncontrolled debris field/Spacecraft damage	The spacecraft and its sensors and instrument suite is being damaged by the falling debris.	4*3= 12	Spacecraft landed at safe angle, No direct line of sight, event horizon
[5] Unable to detect large enough boulder/rock for anchoring	The onboard sensors/instruments cannot detect a suitable bolder to start the anchoring approach.	4*4= 16	Will be answered by MMX, increase search and overfly time.
[6] Spacecraft unable to Anchor to Bolder	The Spacecraft is unable to anchor to the target bolder. Even after repeated tries	3*4= 12	Back-up target will be targeted, and the propellant reserve is large enough to cover more than one anchoring approach.

The risk square has also been updated to show current risks and their positions (*Figure 20*).

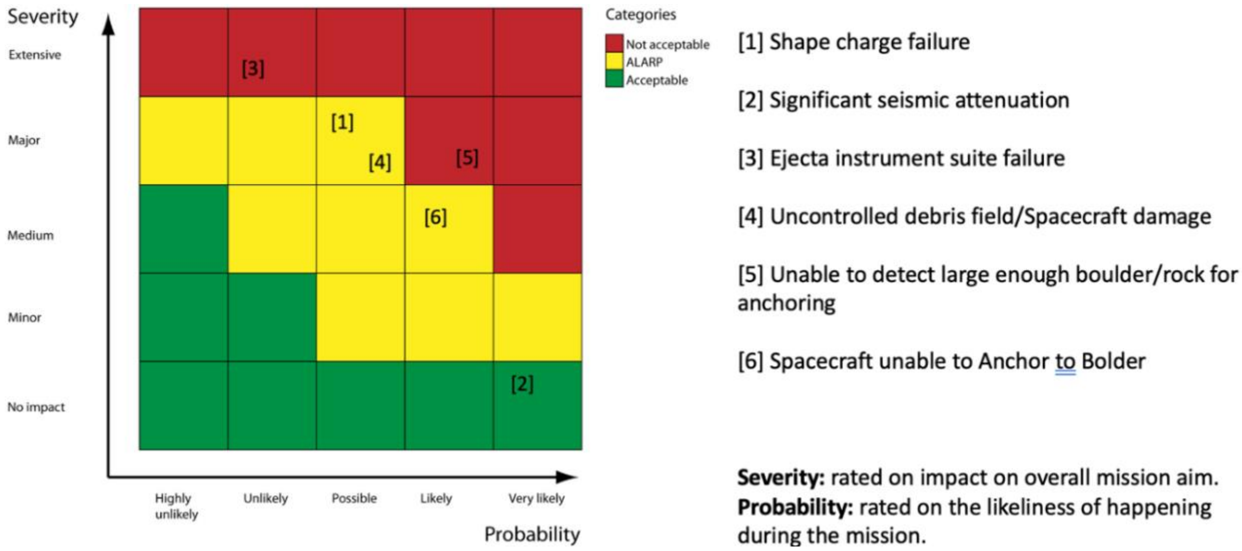


Figure 20: Updated risk square.

Cost

Similar missions and programs are used as a comparison to estimate the approximate mission budget. At this point in the development of DREAM, the goal is to ensure that the scope of the proposed architecture is in line with what other missions have accomplished and that the dollar target fits into that category. Since this is a rough order-of-magnitude estimate, the order of magnitudes and their associated mission capabilities must be understood.

Large programs, such as Apollo or Artemis, are at the top of the cost scale, where the total cost will be tens of billions of dollars (adjusted to the present day). A step below this is NASA's Large Strategic or Flagship-class missions, such as the James Webb Space Telescope, which cost from $1 to $10 billion. Next is the New Frontiers program, including New Horizons or Osiris-Rex, which cost $500 million to $1 billion. The Discovery class program includes relatively small missions led by a principal investigator, costing $100 to $400 million. Explorer class projects come in at a few million dollars each. Finally, at the bottom of the cost scale are university-lead projects that launch cube sats for between $20 to $90 thousand.

DREAM targets to have capabilities and science objectives that fit in the NASA Discovery-class mission. The Discovery program constrains the mission budget to $190 million for prelaunch development and $299 million total (Williams, 2023). Discovery missions are often focused on a specific objective. Examples of past missions that have been funded within this class include Lucy, Psyche, InSight, LRO, Kepler, Dawn, and Deep Impact. The renderings of these missions can be seen in Figure 21. Interestingly, the Discovery program can include Missions of Opportunity, which fund US involvement in international missions (for a smaller dollar amount) and two instruments for MMX are currently funded by NASA under the Discovery Program.

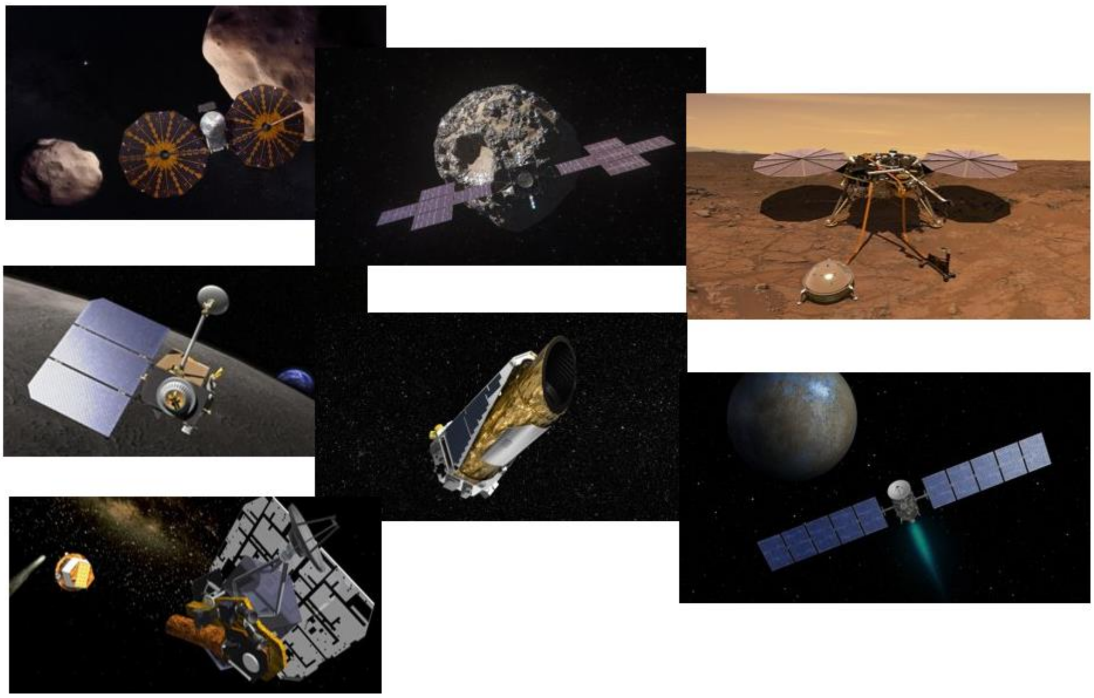


Figure 21: Renderings from example Discovery Class missions.

Table 11: Cost structure of DREAM.

Cost Structure Proposed	
Spacecraft bus	$50M
Scientific payload	$20M Reduced Instrument suite
Shaped charge system	$15M
Anchoring technology	$10M
Geophone array	$5M
Launch vehicle	$80M Small launch vehicle
Operations cost	$50M
Reserves:	$10M
Pre-launch development costs	**$190M**
Post-launch costs	**$109M**
Total	**$299M**

Table 11 depicts the anticipated costs for DREAM with the following assumptions:

- Spacecraft bus based on past Discovery mission costs
- Scientific payload estimated based on instruments proposed
- Shaped charge, anchoring technology, geophone costs estimated
- Launch costs estimated for the small-medium-class launch vehicle to reach escape velocity and transfer orbit insertion
- Operations costs estimated based on mission duration
- Reserves at 5% of development costs

Given the cost cap of $299M, a mission to meet the defined objectives is feasible within that budget envelope. The estimate would be refined through a detailed design process to meet the exact cost cap. Launch vehicles, operations costs, and the shaped charge and robotic arm currently have the most considerable uncertainties.

Next Steps

The Colorado School of Mines SPRS 592 module presents an excellent opportunity to further develop the DREAM mission concept into a more detailed technical project. The additional engineering design work possible in 592 can mature the mission from a conceptual state into a fully preliminary design supported by analyses and simulations.

One major avenue for refinement is to create high-fidelity CAD models of the DREAM spacecraft and all its subsystems, including deployable items like the shaped charge, anchoring arms, and geophone array. Photorealistic renders of the spacecraft can then be generated to aid in mission visualization. Detailed subsystem sizing can be performed using these models to provide an updated master equipment list and mass budget. Power, thermal, and structural analyses of the spacecraft bus and scientific instruments will verify their ability to operate in the environment near Deimos. The operations concept and CONOPS can also be elaborated based on updated spacecraft capabilities and constraints.

The anchoring methods require additional analysis to optimise the design. Physics-based simulations of the robotic arm dynamics and regolith interactions will enable assessing anchoring performance with different boulder shapes and compositions. The control algorithms for the anchoring operations can also be prototyped and refined. Similar dynamics analyses are needed for the shaped charge detonation and seismic wave propagation through simulated Deimos interior models. Waveform attenuation behaviour through porous regolith structures needs quantification to demonstrate DREAM's capability to map the deep interior.

Physical testing is another avenue for maturation in 592. Anchoring prototypes could be tested in low-gravity aircraft or planetary surface simulant testbeds. Sample-shaped charges can be detonated at CSM's explosives lab to characterise the ejecta material and seismic output. The lab's spectral instruments for plume analysis can be demonstrated with analogue ejecta samples.

Finally, the SPRS 592 project effort should produce detailed documentation on the mission design, illustrative renderings and animations, and potentially a conference paper or competition submission. The hands-on engineering design, analysis, simulation, testing, and documentation completed will significantly advance DREAM from a concept to a credible preliminary design.

Conclusion

The Deimos Resource Exploration and Anchoring Mission (DREAM) provides an impactful and cost-effective approach to advancing capabilities needed for future in-situ resource utilisation activities on Mars and its moons. By concentrating on a set of focused payload elements and technology demonstrations, DREAM can reveal Deimos' resource potential and engineering challenges associated with operating on small planetary bodies.

DREAM's scientific instruments, including spectrometers, cameras, and a seismic survey, will analyze the composition of Deimos' surface and interior to identify resources for extraction. The mission instruments can quantify the presence of valuable materials like heavy metals and hydrated mineral ores within the regolith and subsurface. Demonstrating two different anchoring methods to surface boulders and regolith will also test critical technologies for prolonged interaction with the surface.

The mission architecture centers on proven approaches, such as a single spacecraft with deployable elements, to reduce complexity and maximize reliability. The streamlined concept meets Discovery program cost caps by focusing payload and operations on key mission priorities. DREAM will gain critical insights into Deimos' formation history and structure and demonstrate technologies like seismic surveys and surface anchoring that enable more ambitious future exploration.

As a pathfinder for more extensive resource mapping and utilization missions, DREAM offers substantial returns on a limited budget. The knowledge and capabilities gained will inform human missions to Mars, seeking to leverage local resources and anchoring. By comprehensively probing Deimos with an optimized instrumentation suite, DREAM lays the groundwork for the space resources economy of the future. The mission could transition resource prospecting from speculative concepts into actionable engineering projects from in-situ materials. The DREAM mission concept opens the door for Mars system exploration driven by utilizing local resources. *DREAMing* of peaceful human exploration into space.

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