Colorado School of Mines
SPRS 592
Spring 2024

Mars Moon Resource Mission

DREAM

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

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Submission Date
6 May 2024

Abstract

The Deimos Resource Exploration and Anchoring Mission (DREAM) is an exploratory mission that aims to evaluate the Martian moon Deimos's resource potential and engineering challenges 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 ejecta plume from an impactor. 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, as well as future habitat building on other lower-gravity bodies, will be demonstrated with micro spine grippers. The full mission architecture has been estimated and modelled on a broad scale. The streamlined and specialized payload and chosen 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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Science Background

Phobos and Deimos are two moons that orbit around Mars. Similar to Earth's moon, they always show the same side to Mars and are small and lumpy in shape. While these moons are similar in some respects, some individual features make them unique. These differences were studied, focusing on possible formation theories and the resources these moons could yield.

Phobos [Figure 1] is the larger moon with dimensions of 27 by 22 by 18 km, while Deimos [Figure 1] is smaller at 15 by 12 by 11 km [(In Depth | Phobos, n.d.), (In Depth | Deimos, n.d.)]. Phobos orbits three times a day and is on a collision course with Mars, moving closer at a rate of 1.8 m per hundred years. Phobos has a circular, low inclination, prograde, and equatorial orbit with a location just outside the Martian Roche Limit (Sercel, et al., 2018). Deimos orbits every 30 hours with the same orbital characteristics as Phobos. However, Deimos is moving outwards from Mars and is located just outside Mars synchronous orbit (Sercel, et al., 2018). Both moons are tidally evolved, have no atmosphere, and have minimal gravity. Images of the moons show that there are fairly large boulders on the surface of ~40-60 m, and they are likely highly porous rubble piles. Phobos has grooves, ridges, and a 9.7 km wide crater named Stickney crater. Deimos is expected to have a thick regolith with dust propelled from impact cratering and redeposited on the Martian moon's surface.

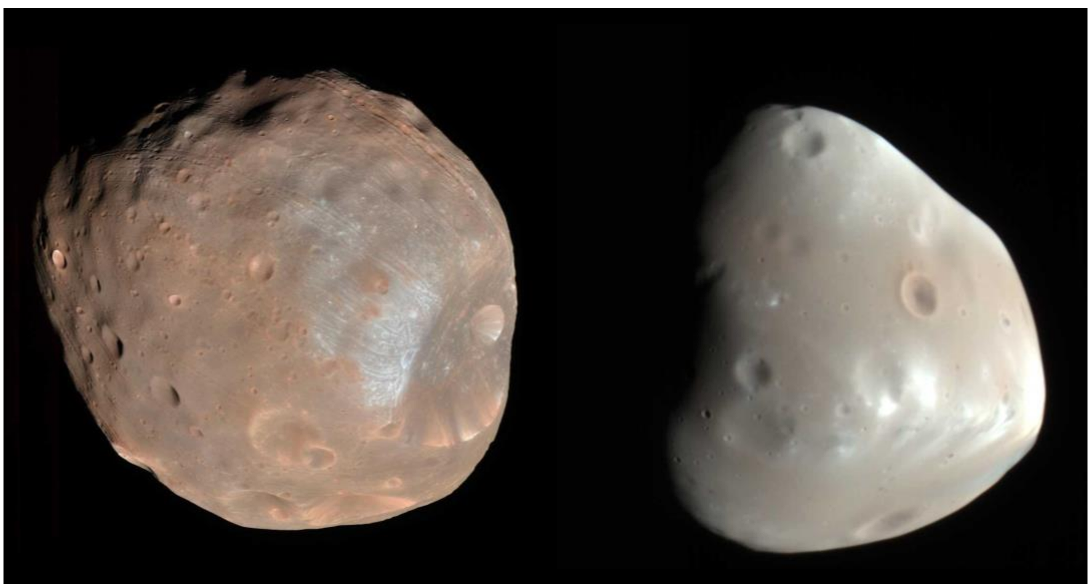

Figure 1: Image of Phobos (left) and Deimos (right, color-enhanced) taken from NASA's HiRISE camera on MRO [(In Depth | Phobos, n.d.), (In Depth | Deimos, n.d.)].

Research into formation theories on Phobos and Deimos resulted in numerous ideas. Two main theories were the most prominent: asteroid capture and formation through a circum-Mars accretion disk [(Sercel, et al., 2018), (Ramsley & Head, 2021)]. First, many agree that this theory is unlikely when looking at asteroid capture. This is largely based on the orbit characteristics of the moons. While some surface spectra characteristics resemble C- or D-type asteroids, among other spectral data, the models attempting the capture and subsequent orbit stabilization for the moons up to present day do not work. Additionally, asteroid capture does not support Phobos slowly moving inwards towards Mars. The most convincing piece of evidence is that with asteroid capture, it is very likely that the two moons would have collided with each other. Moving towards the circum-Mars accretion disk theories, there are three main theories: (1) a primitive asteroid 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 & Head, 2021)], or (3) formation occurred in the early solar system from a primordial circum-Martian disk (Ramsley & Head, 2021). The first theory has been determined to be dynamically improbable, while the third theory has issues when it comes to dating Phobos' orbital decay back to stating time that post-dates the solar system's formation. Ramsley and Head believe that an impact to Mars is more likely the cause of formation over the co-accretion theory.

When considering the resources that could be seen on each moon, it can be highly dependent on which formation theory is favored. One major influence on this would be the degree of heating that is experienced in each process. 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 (carbon-rich organics, iron oxides, hydrated phyllosilicates). Volatiles will likely have a lower abundance potential while phyllosilicates may have survived, leading to resources such as hydrogen and oxygen, organics from carbon compounds, iron oxide, and mafic structures. 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 this process means that the moons would not be hydrated but would contain high-temperature iron- and magnesium-rich silicates and dehydrated and metamorphosed phyllosilicates.

Mission Objectives, Overview, and Key Decisions

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 towards 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). This statement created an initial mission concept, and the considerations are summarized.

As touched on in the scientific background section, various resources that could be achieved from the Martian moons are water, propellant storage, a mining testbed, raw minerals, bulk regolith, a Mars staging area, and sand breaking. The authors believe that the first resources to be utilized from the moons of Mars will be in the service of Martian exploration.

The next decision to be made was to pick if the spacecraft would visit Phobos, Deimos, or both. After preliminary research, it was found that a Japanese spacecraft called MMX (Martian Moons eXploration) is to travel to and explore the moons in the new few years. However, this mission will primarily focus on Phobos. This mission, among other factors, caused the decision to be made that DREAM will focus solely on Deimos, the less explored of the two moons (more of analysis on alternatives in (Ellingson, Needler, Stolov, Dorogy, & Freiherr von Suesskind, 2023)). In addition to only exploring Deimos, it was decided that there would be no sample return. Sample return make the mission more complicated, and MMX will be completing a sample return from Phobos. While the moons likely have minor differences, it is probable that the composition of the moons is similar and a sample return from Deimos would be redundant.

Moving to the mission objectives, DREAM's 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. This involves analyzing an ejecta plume from an impactor, performing a seismic survey, and demonstrating anchoring techniques.

Anchoring

Any future ISRU operations with a low gravity body such as Deimos requires the technology to interact with a surface. Excavation and construction necessitate high loads that are typically reacted by gravity. One of DREAM's primary objectives is to demonstrate an anchoring approach to develop a state of the art for working with low gravity rubble piles. This is accomplished using a microspine gripper mechanism that has been shown to provide significant holding force on uneven, rocky surfaces. More details on the anchoring approach is covered in the Mission Design Elements section of the report.

Instrumentation

Given the scientific objectives of this mission, the instruments were selected in order to achieve mission goals. These instruments will be involved in completing numerous mission operations, including navigation, site selection, analysis of the ejecta plume, mapping of the moon's surface, obtaining high-res images, and more. Previous missions with similar goals were analyzed in order to select the appropriate instruments that would lead to successful results, as well as instruments that can be used in multiple operations. This allows for less volume and weight to be allocated towards instrumentation and can decrease mission cost.

The missions that were researched were OSIRIS-REx, LCROSS, and MMX. OSIRIS-REx traveled to the asteroid Bennu with the objectives of mapping and analyzing the surface. The instruments that were used for this mission included a camera suite of varying ranges, a laser altimeter, a thermal emission spectrometer, a visible and infrared spectrometer, an x-ray imaging spectrometer, and a redundant navigation system (OSIRIS-REx Mission, n.d.). LCROSS aimed to determine if water-ice is present on the lunar poles and utilized an impactor to create an ejecta plume. The main instruments were a visible camera, near infrared cameras, mid infrared cameras, a visible spectrometer, near infrared spectrometers, and a total luminescence photometer (LCROSS, n.d.). Finally, MMX is an upcoming mission which aims to determine to origin of Phobos and Deimos, with the focus being mostly centered around Phobos. The planned instruments for this mission are two cameras of varying ranges, a laser altimeter, a near infrared spectrometer, an ion mass spectrometer, and a gamma-ray and neutron spectrometer (Kuramoto, et al., 2022). Further in-depth review and analysis of these missions and instruments can be seen in (Ellingson, Needler, Stolov, Dorogy, & Freiherr von Suesskind, 2023).

Table 1: Instrument selection for DREAM.

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 for seismometer
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 seismometer placement, 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 an 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 observations of impact sire before impact, gather data from ejecta plume

After reviewing these previous missions in depth, it is clear that a few of these instruments are standard for exploratory missions, as well as used in operations that are similar for this planned Deimos mission and can be incorporated directly or adapted to suite this mission’s needs. A mix of spectrometers and cameras can be seen in every mission, as well as laser altimeters due to their navigational purposes. A majority of the DREAM instrument suite took inspiration from OSIRIS-REx as the mission objectives were quite similar and the instruments could serve numerous purposes. In total, 10 instruments were selected for DREAM, consisting of two laser altimeters, five cameras, and three spectrometers. Table 1 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

In order to determine structure and compositional differences, seismology can be used. MMX will be analyzing the surface of Phobos and DREAM will be looking at the surface and near sub-surface of Deimos through the ejecta plume analysis. However, data on the subsurface can also hold significant information, both about the resources that could be present as well as information that may help to define the true formation theory of the moons. More detail on the seismology process is discussed in the next section.

Seismology on Deimos

Understanding the deep interior structure of small planetary bodies (SPB) is critical to fully characterizing resource distribution in our solar system. To image the deep subsurface, we commonly use radar or seismic methods. Radar measures the dielectric properties of a material and is sensitive to changes in the near subsurface. Although radar can operate from orbit, thus avoiding the complexity of coupling in microgravity, attenuation effects are significant in rubble piles and rocky bodies, limiting penetration depth to within several wavelengths (Haynes, et al., 2020). Seismic imaging, however, measures the mechanical properties of a material and is sensitive to variability in the deep subsurface. This means that seismic waves can penetrate through rubble piles without significant attenuation.

We anticipate that Deimos has mechanical properties consistent with previously observed small bodies that would cause substantial radar attenuation. For this reason, we propose that the main objective of our mission should be dedicated to the seismic exploration of Deimos. The top-level objectives of this mission are broken into key components in Table 2.

It is important to note that without a dedicated mission, it is impossible to confirm the propagation of seismic waves on Deimos or other SPB's (Courville, et al., 2021). Determining whether this energy can propagate in the subsurface is foundational for our understanding of grain interactions and cohesion (Ellingson, Needler, Stolov, Dorogy, & Freiherr von Suesskind, 2023). Barring known instrument failures, if seismic events cannot be reliably detected, we believe the exploration would still be considered successful since it provides us the opportunity to infer and constrain interior properties. Moreover, if DREAM is able to detect natural seismicity, the mission would also yield insight into interior dynamics and processes that are otherwise unobservable with remote sensing methods.

Table 2: Objectives of seismic exploration of Deimos.

	Description	Importance
O1a	Determine if seismic energy propagates on SPB's.	Primary
O1b	Characterize seismic propagation in SPBs. Infer particle interactions.	Primary
O2	Construct a preliminary velocity model of Deimos (i.e. subsurface tomography).	High
O3	Estimate seismic attenuation in SPB's.	High
O4a	Observe and characterize natural seismic activity, if present.	Medium
O4b	Infer dynamic interior processes (resorting, rock falls, tidal deformations, etc.)	Low
O5	Constrain particle cohesion and friction in small bodies.	Medium

Seismic exploration has only been conducted on three planetary bodies: Earth, the Moon, and Mars. Thus, a dedicated mission to explore SPB seismicity can be considered a significant new scientific contribution that would allow us to understand planetary formation and evolution better, as well as resource distribution in our solar system. In the subsequent sections, we provide information on the source and receiver, hardware deployment, and anticipated acquisition for the proposed seismic exploration of Deimos.

Active source impactor

Active source seismic exploration relies on the controlled generation of energy waves to probe subsurface structures. To produce this energy, we use active sources that serve as the initiator of seismic waves. The selection of an appropriate energy initiator is of paramount importance and is intricately tied to the objectives of the exploration mission. Firstly, the source must be capable of generating seismic waves with sufficient strength to penetrate through the various geologic features encountered in the subsurface. The signal strength directly influences the quality and depth of data collected, thereby determining the feasibility of subsurface imaging. Higher frequency sources offer a finer resolution, enabling the detection of smaller-scale features within the subsurface. Conversely, lower frequency sources are adept at penetrating deeper into the Earth, albeit at the expense of resolution. Thus, selecting the active source requires balancing the desired resolution and depth of investigation. In terrestrial exploration, explosive sources such as dynamite provide a sufficient frequency band range to penetrate deep into the subsurface while also imaging small-scale features in the near subsurface. Other common alternatives include mass-drop sources and vibrational pads (vibroseis). Although not feasible on Earth, kinetic impactors could be used as seismic sources in the SPB exploration setting. However, the complexity of launching prior to landing, selecting an orbit that allows the spacecraft to land first, and the risks associated with the debris field are large and cannot easily be reduced. Moreover, sources launched from a mortar on the surface-- after the spacecraft has landed-- are limited by Deimos's low escape velocity and cannot produce sufficient impact energy (comparable to a small amount of TNT at more than $1E3$ J) for seismic data acquisition even when fired into a retrograde just below escape velocity. For these reasons, we have chosen an active explosive source that minimizes launch mass and mission complexity.

Table 3: Characteristics of seismic propagation for a 10 Hz source travelling in 3 different media. The seismic response of Deimos is almost entirely unconstrained. Adapted from (Ellingson, Needler, Stolov, Dorogy, & Freiherr von Suesskind, 2023).

	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

We propose that the explosive source be launched during the approach to Deimos. This approach serves two goals. First, a launch from orbit will allow the impactor to produce a small debris field that can be analyzed with onboard spectroscopy and optical imagers without producing a dangerous debris cloud. Second, a "bunker buster" impactor allows us to drive the explosive below the surface so that energy transfer to the surrounding particles is maximized. This further improves the source energy and boosts the signal-to-noise (SNR) ratio during data acquisition. To control the debris cloud created by impact, the launch velocity should be on the order of 10's of meters, although an exact threshold cannot be determined without the better understanding of surface cohesion that will be provided by MMX. Once the spacecraft has anchored to the surface and deployed the seismometer, the implanted explosive source can be detonated to perform the active seismic acquisition.

Receiver design

To balance launch mass constraints with the mission science goals, we suggest using a single, three-component (3C) broadband seismometer similar to the Martian InSight Seismometer. With this configuration, we will be able to detect events between 0.1 - 1 Hz in the horizontal plane and 0.01 -1 Hz in the vertical axis (Longonné, 2019). Although this instrument design has been tailored for the InSight mission, we believe this frequency range is sufficient for deployment on Deimos since the assumed Deimos geology would not attenuate strongly in this frequency range. However, if the MMX mission observations suggest otherwise, the peak frequency range may need to be tuned to account for those observations. Without new findings provided by MMX, we do not have sufficient information on SPB particle properties to require a new instrument design.

If mission mass requirements are loosened, we would suggest the addition of several more seismic stations to improve SNR and enable more advanced data analysis. However, even with a single station, an active source enables us to invert the travel time between the source location and receiver position to estimate a velocity model of the intermediate subsurface.

Extended discussion of the deployment of the seismic array is deferred until we introduce the deployment mechanism. Still, we note here that seismic coupling to Deimos is non-trivial but vital to successful observation. To achieve high-quality seismic data, the seismometer must always remain coupled to the surface. Any uplifting of the instrument will render it incapable of detecting seismicity because it is no longer in contact with the surface where the seismic energy propagates. This is a known potential issue for SPB's with low gravity. To overcome this issue, our seismometer will be emplaced and held to the surface with the robotic arm of the DREAM spacecraft. Since we "anchor" the seismometer with known force, we can account for the arm's transfer function to the recorded energy. Although observations from the Apollo and Viking missions suggest close proximity to the spacecraft is determinantal to the recorded energy, we believe the atmosphere-less environment of Deimos and distance from the sun, in conjunction with quiet periods for the onboard electronics, will allow us to circumvent the issues that plagued previous missions (Lorenz, Nakamura, & Murphy, 2017).

Quiet periods may be particularly important for continued seismic observations of natural ambient seismicity on Deimos. Tidal deformations, thermal gradients, the YORP effect, and numerous other mechanisms are potential causes of seismic wave propagation on SPBs like Deimos. By listening for these natural sources after the initial experiment, we can continue to image the subsurface using these secondary events to replace our active sources, albeit with a significantly lower SNR. Observing these naturally occurring events, if they exist, also provide a second manner by which to understand the subsurface. For example, seismic recordings of interior resorting provide another opportunity to understand interior sorting and dynamics.

Mission Design Elements

A CAD design of the DREAM spacecraft was created to help refine the mission architecture and concept. The realistic sizing of key design elements in the CAD design helps support the mission's feasibility. A rendering of the design is shown in Figure 2.

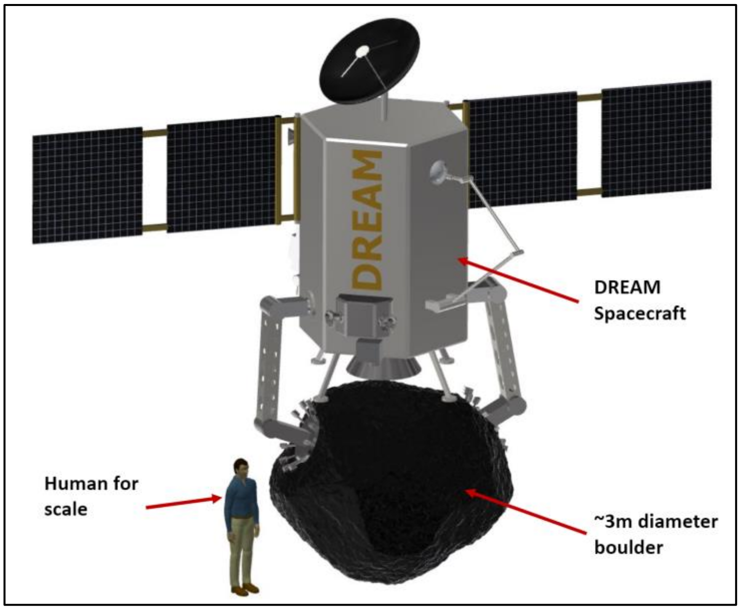

Figure 2: CAD Design of the DREAM spacecraft over a notional 3m diameter boulder. The human shown for scale is 6' tall.

Based on this conceptual CAD, the estimate of the spacecraft's size is about 2.5 x 2.5 x 3.5 meters in the stowed configuration (without the solar panels and legs deployed), which is similar in size to the Osiris Rex spacecraft (Beshore, 2015).

The anchoring elements, highlighted in Figure 3, are one of the spacecraft's most important and defining features.

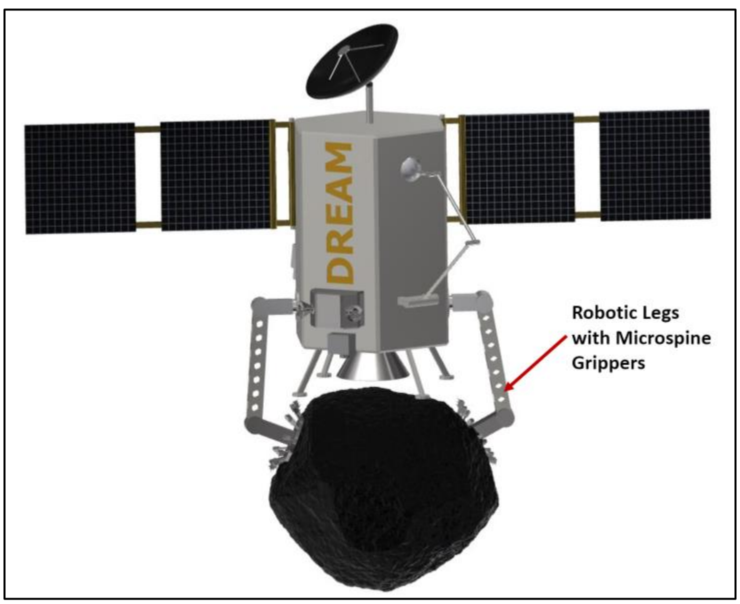

Figure 3: CAD diagram of the DREAM spacecraft highlighting the anchoring elements, which consist of two robotic legs with micro spine grippers as the end effectors.

The design of the anchoring elements is the result of literature review and a trade study summarized in previous work (Ellingson, Needler, Stolov, Dorogy, & Freiherr von Suesskind, 2023). The result of the work was the selection of one of the more developed concepts of using micro spine grippers at the end of a robotic arm. This is similar to the architecture developed for the Asteroid Redirect Mission, in which a spacecraft would “land” on an asteroid, grab onto a boulder of appropriate size, and take off to continue on its mission (Muirhead, 2014). An illustration of this is shown in Figure 4.

Figure 4: Artist rendering of the Asteroid Redirect Mission spacecraft grabbing a boulder from the surface of an asteroid (Gates, 2016).

The DREAM anchoring architecture has several key differences. The low surface gravity and rubble pile structure of asteroids and Deimos makes “landing” on the surface not feasible and an incorrect descriptor of spacecraft operations. Additionally, there is no guarantee that a boulder that is large enough to grab but also small enough to wrap around is available and accessible on the surface. DREAM seeks to anchor to the boulder without the requirement to take off again. The DREAM spacecraft requires a minimum boulder size of about 1.7 meters in diameter to remain on the surface and conduct surface operations without being pushed away. The estimated reaction loads and boulder size calculation is summarized in the previous report (Ellingson, Needler, Stolov, Dorogy, & Freiherr von Suesskind, 2023).

The selected anchoring concept is the micro spine grippers, shown in Figure 5.

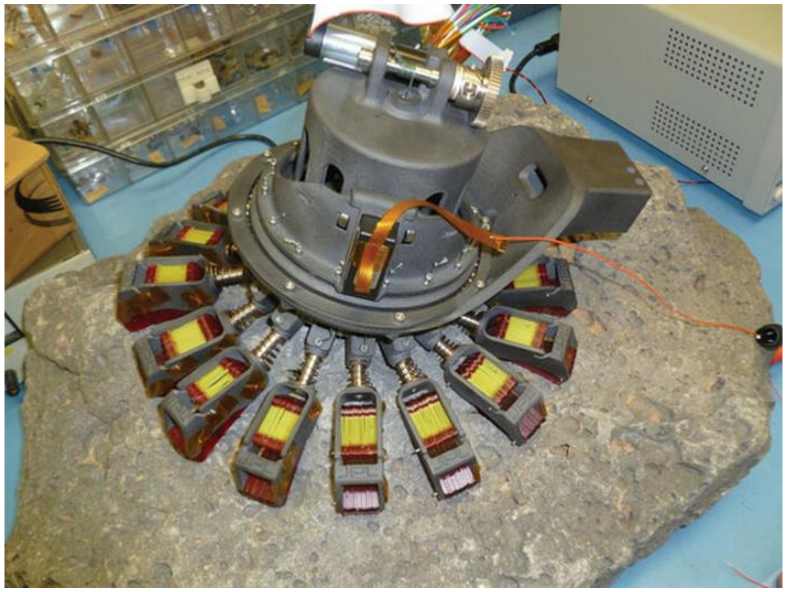

Figure 5: Testing of the micro spine gripper design on a natural rock (Parness A. M., 2012).

Micro spine grippers, shown in Figure 5, were down-selected as the anchoring concept. This concept has been tested on various natural rocks and demonstrated to hold significant load (Parness A. M., 2013). While these grippers are dependent on a rocky surface, they are the most advanced option and reduce development time and risk compared to other options. The trade study for the anchoring down select is summarized in the previous report (Ellingson, Needler, Stolov, Dorogy, & Freiherr von Suesskind, 2023).

Once anchored on the surface, DREAM will deploy the seismometer using a robotic arm (shown in Figure 6).

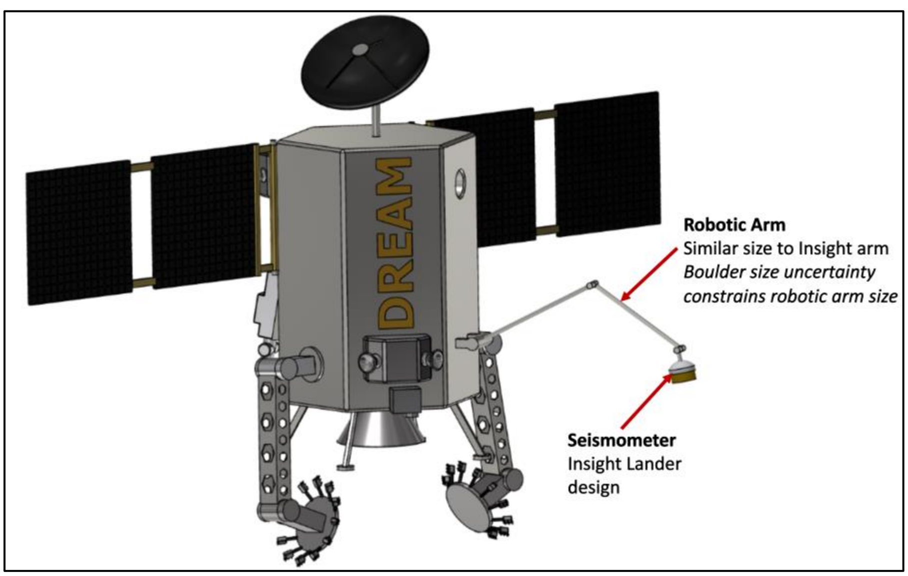

Figure 6: CAD diagram of DREAM highlighting the robotic arm deploying the seismometer.

The robotic arm and seismometer design, shown in Figure 7, is based on the Insight Lander architecture in terms of sizing and degrees of freedom. These elements are some of the highest heritage hardware on DREAM.

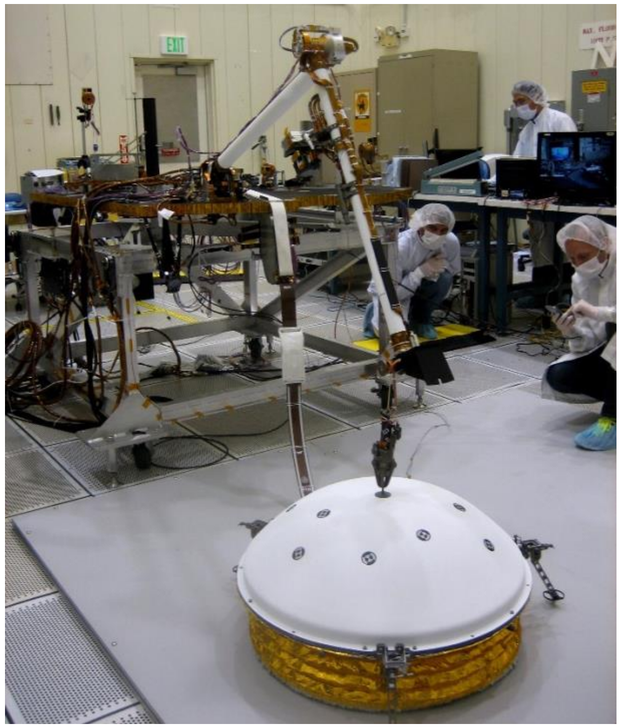

Figure 7: Testing of the robotic arm and the seismometer that were both successfully operated on Mars by the Insight Lander (JPL, NASA Jet Propulsion Laboratory, 2015).

A key difference is that the DREAM robotic arm must preload the seismometer against the surface of Deimos to ensure it is physically coupled in the low-gravity environment. However, there is no guarantee that the arm is capable of preloading against a regolith surface rather than the surface of the boulder the spacecraft is anchoring to. Figure 8 shows a CAD representation of DREAM anchored to a boulder approximately 10 meters in diameter.

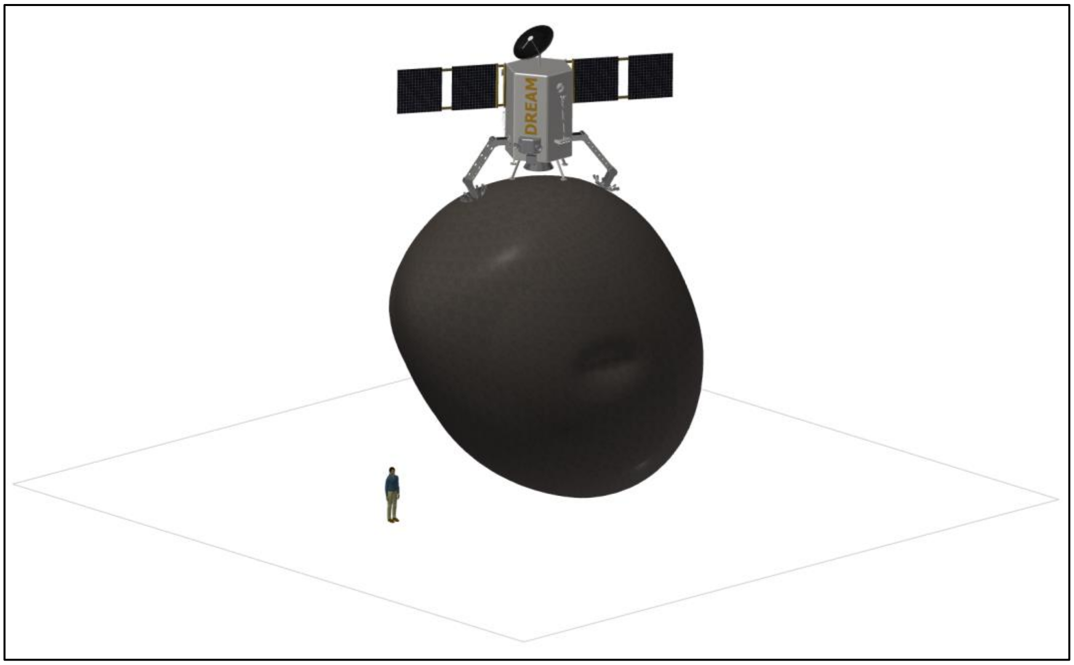

Figure 8: CAD representation of DREAM anchored to the top of a boulder approximately 10 meters in diameter.

The size of the chosen boulder for surface operations is key to consider in developing the DREAM architecture. The best indication of the existence of boulders on the surface is an image taken from the Viking 2 Orbiter, shown in Figure 9. Several boulders 10-30 meters in diameter are visible in the image, indicating that there may be several targets of that size to choose from.

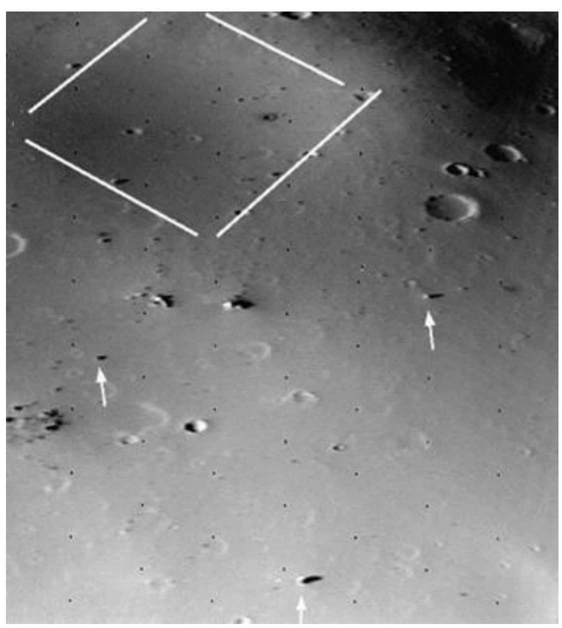

Figure 9: Surface of Deimos imaged by the Viking 2 Orbiter. The image covers an area of approximately 1.2 km x 1.5 km. Arrows point to boulders 10-30 meters across (Williams, 2015).

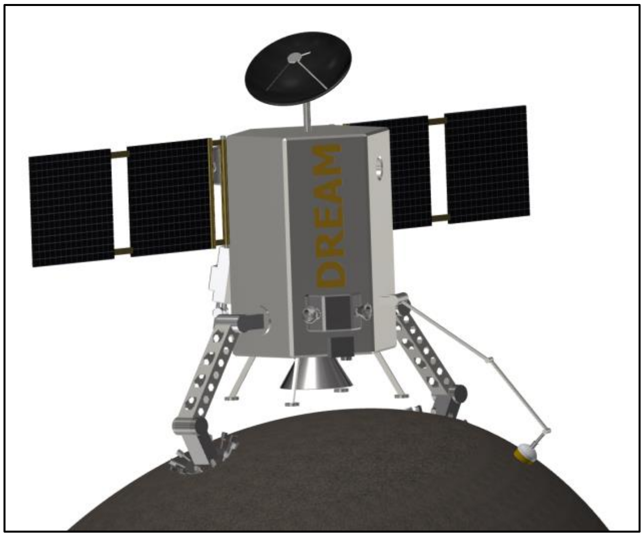

Figure 10: CAD diagram showing the DREAM robotic arm deploying the seismometer and preloading it against the surface of the anchored-to boulder.

In anchoring to a boulder 10+ meters in diameter, the robotic arm may have to be greater than 10 meters in deployed length when fully deployed, which imposes unrealistic requirements on the mission. Instead, DREAM will baseline preloading the seismometer against the anchored-to boulder and will constrain the robotic arm to a size based off the Insight Lander arm.

The spacecraft will also host several science payloads, several of which have been added to the CAD for sizing estimates (Figure 11).

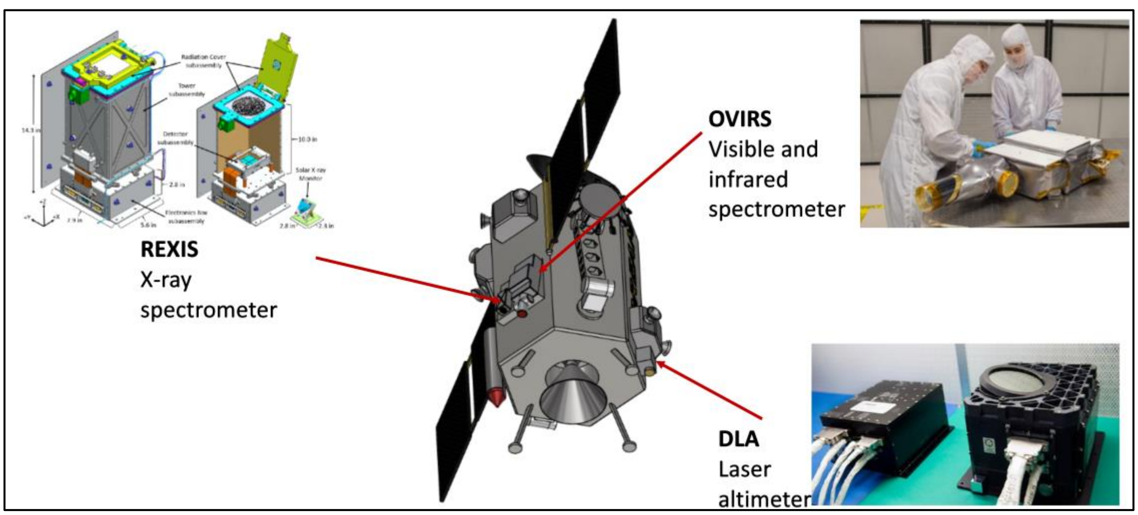

Figure 11: CAD Diagram highlighting several remote sensing science instruments selected for the DREAM mission. Instrument sizes were based on publicly available data on the corresponding instrument. Top Left: REXIS X-ray spectrometer (Masterson, 2018). Top Right: OVRIS Visible and infrared spectrometer (Reuter, et al., 2018). Bottom Right: DLA Laser Altimeter (Daly, 2017).

Of note, the Laser Altimeter is oriented downward as it also assists with approach anchoring operations in addition to its primary function of mapping the topography of Deimos. Spectrometers can be oriented at a downward angle also to be able to analyze the surface of Deimos while anchored in addition to their remote sensing requirements.

Some important elements of the DREAM spacecraft are highlighted in Figure 12. DREAM uses deployable solar panels for power and a communication antenna for direct-to-Earth communication. A main thruster provides the major burns required for the mission, while RCS thrusters assist with minor corrections and with a gentle, controlled approach to a boulder for anchoring. Legs around the main thruster protect the nozzle from bumping up against the surface during anchoring. While these elements are important for sizing and general mission architecture, the development of these subsystems are not the focus of this report.

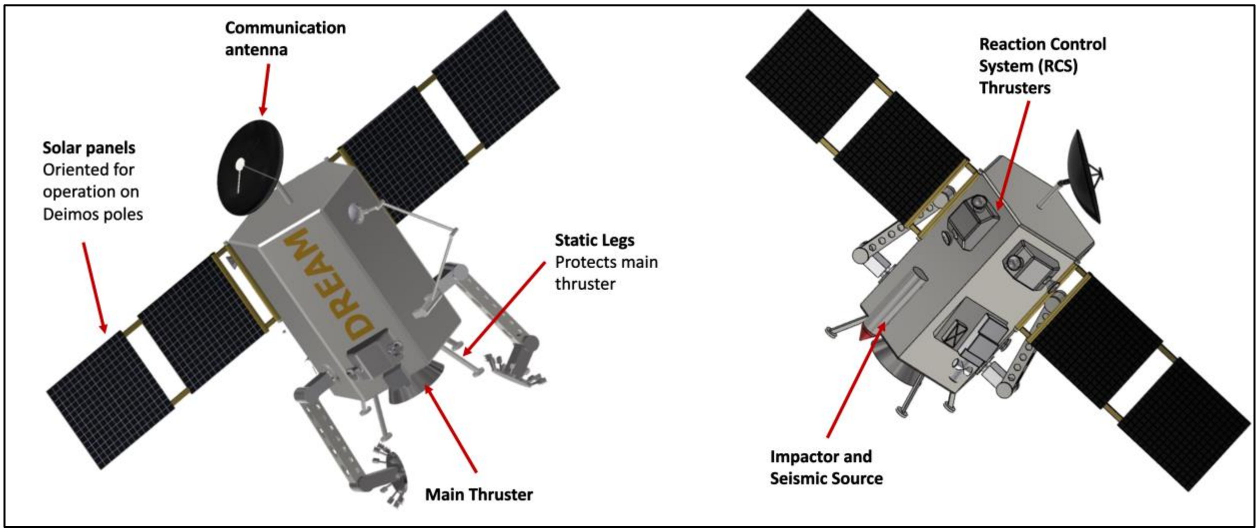

Figure 12: CAD diagram highlighting some additional high level design elements of DREAM.

A major element to highlight is the impactor and seismic source, which is released from the spacecraft before orbital insertion. The impactor must be heavy enough to provide enough potential energy on impact to create an observable plume while at the same time sturdy enough to protect the delayed shape charge inside.

Con Ops

Beginning at launch, the spacecraft will be launched in the chosen launch vehicle out of Earth's atmosphere. The launch vehicle will then put the spacecraft into a Martian Transfer orbit trajectory. This means that the spacecraft will not be using any propellant until reaching the Martian Transfer orbit (excluding minor corrections as needed). The launch vehicle will be providing this delta-v. After reaching the Martian Transfer orbit, the spacecraft will fully turn on and begin to move towards low Deimos orbit.

From here, the spacecraft will orbit around Deimos while completing a few mission objectives. First, the spacecraft will orbit around as much of Deimos as possible and will be mapping the surface. This will allow for composition and abundance maps, topography maps, temperature maps, and more. Additionally, the spacecraft will image and analyze the surface to look for suitable boulders to anchor to. The boulders must be large enough to anchor successfully and be exposed to sunlight. Additionally, the impact site must be far enough away from the anchor site so that the spacecraft would not risk damage, as well as the eject plume must be in partial or full visible light. DREAM will prioritize anchoring locations on either the north or south pole that is closest to the embedded seismic source. The north pole of Deimos has areas of continuous lighting durations of up to 300 days, while the south pole has areas of continuous lighting up to 225 days (Pratt, 2011). This allows DREAM to continue to draw power from solar panels and send more data back to Earth even after primary mission operations. Landing and Anchoring is done autonomously, though the operations and course corrections occur while communications to Earth are active to allow for a delayed response from the ground team. Boulder's approach and anchoring are constrained to a duration of 10 hours to account for Deimos's 30-hour orbital period, which constrains communication back to Earth. Approach and surface operations are shown in Figure 13.

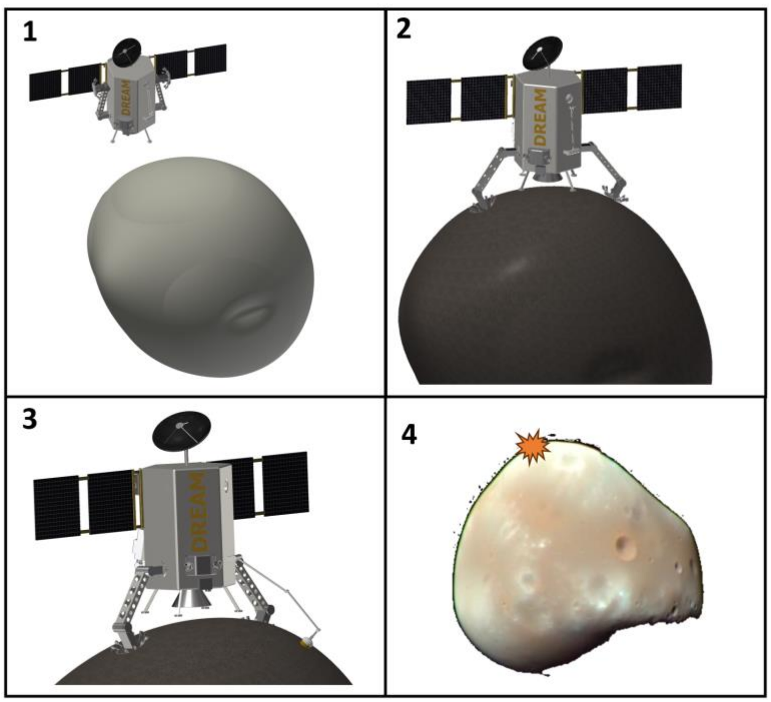

Figure 13: DREAM surface approach and concept of operations. 1: DREAM approaches the target boulder. 2: DREAM deploys the robotic legs and anchors to the boulder's surface. 3: DREAM uses the robotic arm to deploy the seismometer. 4: The shape charge, which is on a timer, goes off and provides a seismic source to be picked up by the seismometer.

Reaction control thrusters and gyroscopes allow DREAM to carefully maneuver to the boulder. The robotic legs are stowed until the approach to the boulder begins so as to not interfere with the science instruments. Upon contact, the micro spine grippers quickly engage and latch to the surface. Once stable, DREAM uses the robotic arm to grab and deploy the seismometer. The robotic arm preloads the seismometer against the boulder, as contact in the low gravity of Deimos would be poor without preload. The seismic contact couples the seismometer to the boulder, which is in contact with the bulk regolith of Deimos. The spacecraft then goes into a "quiet" mode to reduce noise induced into the seismometer. This continues until the delayed charge goes off, which provides the seismic source. To reduce mission complexity, the shaped charge is on a timer, which avoids any development of a communication system that has to survive the impact environment.

This concludes the primary mission operations for DREAM. If successful, DREAM will obtain data on surface and subsurface composition, study the internal structure of Deimos, and demonstrate anchoring and spacecraft surface operations on a low-gravity body.

Mission Sizing

The mission architecture sizing was refined based on the mass and power budget for the science, anchoring, and seismic payloads. The budgets were built based on the book Space Mission Analysis and Design, or SMAD. The tools from this book were used to build out the specifications and sizing for the entire spacecraft. This resulted in a complete mission architecture that included the total payload weight budget, delta-v and spacecraft systems mass budget, spacecraft size and launch vehicle selection, power and comms selection, and basic cost estimation.

Table 4: Power and mass requirements for each DREAM scientific instrument.

Scientific Instruments	Power (W)	Mass (kg)	Source
DLA (laser altimeter)	59	7.6	(OSIRIS-REx Laser Altimeter (OLA), n.d.)
ANC (navigation)	40	6.7	(GSFL-16KS Space 3D Flash LIDAR, n.d.)
LRT (long-range)	5.3	0.6	(OSIRIS-REx Instruments, n.d.)
MRC (medium-range)	5.3	0.6	(OSIRIS-REx Instruments, n.d.)
WAMC (wide-angle multiband)	13	12.13	(Kameda, et al., 2021)
CRC (close-range)	5.3	0.6	(OSIRIS-REx Instruments, n.d.)
NavCam (navigation)	1.3	0.59	(ECAM-C50/M50)
DVS (visible spectrometer)	8.8	17.8	(OSIRIS-REx Visible and Infrared Spectrometer (OVIRS))
DIS (infrared spectrometer)	"	"	(OSIRIS-REx Visible and Infrared Spectrometer (OVIRS))
DXIS (x-ray spectrometer)	8.8	17.8	(Reuter, et al., 2018)
Total	**146.8**	**64.42**	

SMAD utilizes the payload weight to build the rest of the spacecraft specifications. To do this, the payload was defined, and research went into the instruments that make up the payload. They payload consists of the scientific instruments, the robotic arms, and the seismometer. For the scientific instruments, each instrument was based on research from other space missions. Since these instruments were already defined, each one was researched to find the average mass and power. Table 4 shows the mass and power requirements for each DREAM instrument and the total.

Next, the robotic arms and seismometer were investigated to determine their mass and power requirements. The robotic arms were broken up into two categories: one smaller arm for the seismometer and two larger arms that will be used to anchor. Both the seismometer arm and the seismometer were based off research from the Mars InSight IDA (Instrument Deployment Arm) and SEIS (Seismic Experiment for Interior Structure). Table 5 shows the power and mass for each of these areas, as well as the total payload power and mass.

Table 5: Power and mass requirements for each payload classification, as well as the total payload power and mass requirement.

	Power (W)	**Mass (kg)**	**Source**
Scientific Instruments	146.8	64.42	Table 4
Robotic Arms (3) ~ One seismometer arm ~ Two anchoring arms	200	23.8	[(Cruijssen, et al., 2014), (Fleischner, 2013)]
Seismometer	8.5	29	[(Seismic Intruments, n.d.), (A Two-Metre-Long Robotic Arm, n.d.)]
Total	**355.3**	**117.22**	

Now that the total payload mass has been determined, the mass of the spacecraft systems can be calculated. SMAD calculates these system masses based on a certain percentage of the total payload mass. From this, margin and dry mass can be calculated as well. The breakdown of these systems and their mass can be seen in Table 6.

The orbital elements must be considered to calculate the total loaded mass of the spacecraft. This includes the delta-v required to reach the destination, orbit corrections, station keeping, attitude control, margin, and the residual. To find the delta-v required to get to Deimos, the delta-v Map was used (Mars Transfer to Deimos, n.d.). As noted in a previous section, this only accounts for the delta-v that the spacecraft is providing, which involves movements from the Martian Transfer orbit up to Low Deimos orbit and the surface of Deimos. These values are then converted into mass to find the total mass of the propellant, which can be used in conjunction with the dry mass to find the spacecraft loaded mass (Table 7).

Table 6: Spacecraft system and total weight budget.

Element of Weight Budget	Est. % of Payload Mass	Mass (kg)	Notes
Payload ~Science Instruments ~Robotic Arms ~Seismometer	100	**~118** 64 24 30	Instruments: based on other missions (OSIRIS-REx, LCROSS, MMX) Robot Arms: based on Mars Insight IDA Seismic: based on Mars Insight SEIS
Structures	75	88.5	SMAD Table 10-31
Thermal	16.1	19.0	
Power	107.1	126.4	
TT&C	16.1	19.0	
Att. Control	21.4	25.3	
Prop (dry)	21.4	25.3	
Margin	-	168.6	Dry Mass minus all the other items above
Spacecraft Dry Mass	**-**	**590**	Payload is 20% of dry mass
Spacecraft Loaded Mass	**-**	**1696**	Dry + Propellant
Margin as % of Dry Mass	-	28.6%	Margin / Dry Mass

Table 7: Mass budget for orbit and space propulsion of the spacecraft. Assumed the same ISP as OSIRIS-REx engines of ~230s (OSIRIS-REx Spacecraft, n.d.).

Element	Value (m/s)	Notes	Mass (kg)
Martian Transfer to Deimos	1666	SMAD Eq. 17-7, (Mars Transfer to Deimos, n.d.)	744
Orbit Corrections	100	2 years at 50 m/s per year, based on Table 17-1 in SMAD	46
Station keeping	80	2 years at 40 m/s per year, based on Table 17-1 in SMAD and taking a higher value to account for unknowns	37
Attitude Control	185	Assuming 10% of total propellant mass is used for attitude control per Table 17-1 in SMAD	86
Margin & Residual	305 (305)	Assuming 15% of nominal delta-v (sum of above) is needed for margin, per Table 10-7 in SMAD. Residual delta-v isn't ever usable as propulsion	163
Total Nominal	2031	Spacecraft total nominal delta-v	
Total including Margin	**2335**	Spacecraft total delta-v including margin	**1106**

Following the propellant budget, the spacecraft sizing was calculated. In order to pick a launch vehicle, the spacecraft dimensions must be calculated to ensure that the payload can fit securely in the payload compartment. These calculations are based on the spacecraft's loaded weight. Table 8 follows these calculations.

Table 8: Spacecraft volume, dimensions, area, and inertia estimations (SMAD Table 10-28).

Spacecraft Parameters and Characteristics	Estimated	Notes
Spacecraft Loaded Weight (kg)	1696	Table 6, referred to as M below
Volume (m^3)	16.96	$V = 0.01M$
Linear Dimension – Length (m)	2.98	$s = 0.25M^{1/3}$
Linear Dimension – Diameter (m)	3.19	$d = \sqrt[3]{\frac{6V}{\pi}}$
Body Area (m^2)	8.89	$A_b = s^2$
Moment of Inertia ($kg * m^2$)	2412	$I = 0.01M^{5/3}$

Once the spacecraft's length and diameter are obtained, these are used along with the spacecraft's loaded mass to pick an adequate launch vehicle. The Falcon Heavy was selected as the desired launch vehicle. Conflicting information for payload capacity was seen between SpaceX and NASA. The Falcon Heavy webpage claims that there is a capacity of 16,800 kg payload to Mars (Falcon Heavy, n.d.). This means that there would be an excess of 15,104 kg that would be unused and available for a ride-share. Based on this, the Falcon 9 would be a more reasonable choice because the cost would be less and there would still be a capacity of 4,020 kg payload to Mars (Falcon 9). However, NASA's vehicle performance site shows a lower payload capacity to Mars for both launch vehicles (Launch Vehicle Performance Website, n.d.). A C3 (characteristic energy) is required to determine the payload capacity. A C3 of approximately 15 km^2/s^2 is estimated for Mars Transfer (Woolley & Barba, 2022). There is a window of time every 26 months where C3 can drop to a minimum of 8-16 km^2/s^2. With a C3 of 10 km^2/s^2, a Falcon 9 would still have the capacity of 2,220 to Martian Transfer. With a C3 of 15 km^2/s^2, a Falcon 9 no longer has the capacity, and the Falcon Heavy (recoverable) has a capacity of 5,130 kg. Based on the launch window that will be constrained at a later time, it may be possible to use a Falcon 9 instead of the Falcon Heavy. For the purpose of this paper and the current ambiguous timeline, it is assumed that the Falcon Heavy will be used.

Table 9 presents the spacecraft specifications and excess weight margin. The spacecraft will easily fit into the Flacon Heavy payload compartment, which has a height of 13.1 m and a diameter of 5.2 m (Falcon Heavy, n.d.). Based on all spacecraft design constraints, ride-share spacecraft dimensions, and the Falcon Heavy rideshare requirements, the DREAM spacecraft may qualify for a rideshare, which would cut down on the cost of the launch vehicle.

Table 9: Launch vehicle selection and specifications.

Element	Units	Value	Notes
Launch to Martian Transfer	m/s	12,600	This is a rough estimate based on Delta-V Map (Earth to Mars Transfer, n.d.). The launch vehicle will put the spacecraft on a Martian Transfer orbit trajectory. It is assumed that this delta-v is provided by the launch vehicle.
Spacecraft Loaded Mass	kg	1696	Dry mass + propellant, calculated in Table 6
Launch Vehicle	-	Falcon Heavy	Full thrust with drone ship recovery
Payload capacity	kg	5130	Based on estimates from (Launch Vehicle Performance Website, n.d.).
Mass Margin	kg	3434	Can likely be achieved with ride-share on a Falcon Heavy

Next, the power and communication systems were defined further. The total power for all the systems was calculated. This was then doubled to charge the batteries. Since the spacecraft will be in darkness for a good portion of the time, the battery capacity needed is quite high and calls for larger solar arrays. While there is a need for a battery with a significant capacity, it is still expected that there will be adequate lighting on Deimos for the ejecta plume to be in partial or full visible light at some point during the mission's timeline. For the communication system, the telecommunications subsystem for MRO was used (Taylor, Lee, & Shambayati, 2006). This relies on x-band during cruise and operation. While MRO did use other frequency bands, this was for the purpose of demonstration and communicating with landers. DREAM anticipates only requiring x-band for Deep Space Network communication. Table 10 indicates the characteristics and values for the communication and power subsystems.

Finally, the spacecraft cost estimate was completed. Similar to the weight budget, the cost estimate is partially based on the cost of the payload. To start, the payload instrument costs were determined (Table 11). The camera estimations were based on the average price of a single camera that is being used for similar purposes. For the robotic arms, the original asking price for the two arms was used ($33 million in 2016). Since the expected use of the arms is more on the level of the seismic arm and not the anchoring arms, this price for two arms was used for one anchoring arm and split in half for the seismic arm. For the infrared spectrometer, the price was not included as the source found for cost involves a multi-wavelength spectrometer, which could complete both visible and infrared in the same spectrometer. A similar price would likely be seen for an X-ray imaging spectrometer.

Table 10: Characteristics of communication and power subsystems.

Element	Units	Value	Notes
Solar Array Power Output	W	940	EOL power requirement is 470 W. Assumes degradation of 0.8% per year and includes extra panels for charging batteries.
Solar Array Size	m^2	2.66	Total area required is ~2.66 m^2 (assuming 30% efficiency and a solar constant of 590 W/m^2) plus another ~2.66 m^2 to provide extra energy to charge the batteries, per calculations below. Two arrays, symmetrical about the spacecraft and tracking the sun along 1 axis will provide enough power.
Array Weight	kg	18.8	SMAD Table 10-27
Battery Capacity	W-hr	14260	The spacecraft can be in darkness for approximately half it's period, or ~15 hrs. This leads to an energy need of 470 W/hr, assuming a depth of discharge for a nickel hydrogen battery of 50%, (2 years with 1 cycle every period = 30.3 hrs) although for some of each year the spacecraft will actually be in sunlight all the time.
Main Comm Frequency	-	X-band	Frequency of 8 gHz based on MRO.
Radiated Power	W	5	SMAD Table 10-9, small class
Comms Weight	kg	19	SMAD Table 10-31

With a total cost for the payload instruments, a total mission cost before and after launch costs can be calculated. Table 12 indicates that before launch and support, the mission will cost approximately $1.92 billion USD. After including launch and support costs, the total mission cost will be approximately $1.96 billion USD.

Table 11: Cost estimate of the payload instruments. All costs were converted for inflation.

Payload Instrument	**Cost ($M 2024)**	**Source**
DLA (laser altimeter)	72.6	(DeMello, 2014)
ANC (navigation)	72.6	(DeMello, 2014)
LRT (long-range)	3.5	(MSSS to Provide Science Cameras for Janus Asteroid Mission, 2020)
MRC (medium-range)	3.5	(MSSS to Provide Science Cameras for Janus Asteroid Mission, 2020)
WAMC (wide-angle multiband)	3.5	(MSSS to Provide Science Cameras for Janus Asteroid Mission, 2020)
CRC (close-range)	3.5	(MSSS to Provide Science Cameras for Janus Asteroid Mission, 2020)
NavCam (navigation)	3.5	(MSSS to Provide Science Cameras for Janus Asteroid Mission, 2020)
DVS (visible spectrometer)	39.6	(NASA Selects Instruments to Track Climate Impact on Vegetation, 2014)
DIS (infrared spectrometer)	-	(NASA Selects Instruments to Track Climate Impact on Vegetation, 2014)
DXIS (x-ray spectrometer)	39.6	(NASA Selects Instruments to Track Climate Impact on Vegetation, 2014)
Robotic Arms (3) ~ One seismometer arm ~ Two anchoring arms	107.4 (21.5) (85.9)	(SSL Wins $20 Million DARPA Contract to Build Robotic Arms, 2016)
Seismometer	57.0	(CNES To Build Seismometer for NASA's Mars InSight Mission, 2012)
Total	**406.3**	

Table 12: Total mission cost breakdown before and after launch costs (SMAD Table 20-9). TT&C=Telemetry Tracking & Command; ADCS=Attitude Determination & Control System; IA&T=Integration, Assembly & Test; LOOS=Launch & Orbital Operations Support

Subsystem/Activity	Cost ($M 2024)	Notes
Bus Total	1015.8	Payload/0.4
Payload	406.3	Table 11
Structure	185.9	18.3% Bus Total
Thermal	20.3	2.0% Bus Total
Electric Power System	236.7	23.3% Bus Total
TT&C	128.0	12.6% Bus Total
Command & Data Handling	173.7	17.1% Bus Total
ADCS	186.9	18.4% Bus Total
Propulsion	85.3	8.4% Bus Total
Wraps		
IA&T	141.2	13.9% Bus Total
Program Level	232.6	22.9% Bus Total
Ground Support Equipment	67.0	6.6% Bus Total
LOOS	62.0	6.1% Bus Total
Semi-Total	**1924.8**	189.5% Bus Total (exclusive launch/operation costs)
Launch	30	⅓ Falcon Heavy Launch Cost (Reducing the Cost of Space Travel with Reusable Launch Vehicles, 2024)
Operations/Support	3.0	Avg. 50 people at $60,000
Total	**1957.8**	

In order to make sure that the DREAM mission is reasonable, the spacecraft sizing and mission costs will be compared to OSIRIS-REx, LCROSS, and MMX. The cost is expected to be comparable to OSIRIS-REx as DREAM is similar to this mission. LCROSS is expected to vary as it was separated from LRO and the cost will be less for this sub-spacecraft. Table 13 shows that OSIRIS-REx and DREAM are very similar in size and cost. While DREAM is 1.7 times more expensive than OSIRIS-REx, it is not so far over that the cost would be unreasonable. One factor why DREAM may be more expensive is that there are three robotic arms, two of which are more robust in order to successfully anchor to a boulder. This increased the payload instrument cost by 26%. However, while these parts are costly, the arms are a key factor for anchoring to Deimos due to its characteristics.

Table 13: Sizing and cost comparison among multiple missions. Not all costs are in 2024 USD.

Mission	Sizing	Cost	Source and Notes
DREAM	2.98 m tall, 3.19 m diameter, 1,696 kg	$1.96 billion	Table 8, Table 12
OSIRIS-REx	2.4 by 2.4 by 3.15 m tall, 1,955 kg	$1.16 billion	[(OSIRIS-REx Spacecraft, n.d.), (Cost of OSIRIS-REx, n.d.)]
LCROSS	2 m tall, 2.6 m diameter, 891 kg	$79 million	Plus additional funding for delays (LCROSS Quick Facts, n.d.)
MMX	0.231 by 0.376 by 0.415 m, 25 kg	$417 million	Before launch costs [(MMX Facts and Figures, n.d.), (Japan is Sending a Lander to a Martian Moon, and It'll be Back by 2030, 2020)]

Risks

The DREAM mission risk analysis has been monitored and updated throughout the research and development phase of the project. All risks have been listed and mitigated, if possible, during the project. The highest risks, as seen by the DREAM project team, can be viewed in Table 14. It presents the top-level mission risks, their severity and probability, their mitigation strategies, and post-mitigation risk levels.

Due to simplicity and importance grading, only high-level risks of moderate to critical level are shown and mitigated. The DREAM team has analyzed and mitigated all potential risks and dangers to the overall mission objectives (Table 14).

Table 14: Risk analysis DREAM high-level risks.

Risk-Top Level-Critical	Severity & Probability=	Mitigation Strategy	Post mitigation Risk
Shape charge failure	Critical	Mission plan for utilizing seismic data without explosion or impact	Moderate
Significant seismic attenuation	Moderate	Different positions and pressure locations will be tried by the robotic arm	Marginal
Uncontrolled debris damaging spacecraft	Critical	Redundancy in spacecraft system as well as robust design and failsafe's	Marginal
Instrument failure	Moderate	Utilize other instruments, if possible, reinforce their power	Marginal
DREAM spacecraft unable to anchor to boulder	Critical	Enough fuel for another hop to try different locations on Deimos surface	Moderate
No landing location is detected that fits the parameters	Moderate	Touchdown on flat surface rubble, no bolder as grip, reduced mission objectives	Marginal
Detonation/Explosion not strong enough to create seismic waves	Critical	Secondary Mission objectives can still be utilized, sensor suite can be utilized for other objectives aside from the delayed explosion	Moderate
Technical limitation to robotic arm prevents proper geophone location	Critical	Different landing location, boulder must be carefully chosen, engine hop to next location	Marginal
Environment is more harmful than expected	Critical	Mission will be adjusted to end of life calculation, charge and deployment can be speed up	Moderate
Impactor not releasing from DREAM craft during approach	Critical	Mission objectives will be adjusted to secondary; anchoring will be placed on main objective	Moderate
Anchoring fails during grappling and pushes DREAM craft of boulder	Moderate	RCS engines need to be self-stabilizing, main engine is hardened against debris and regolith	Marginal
Anchoring operation tips over the boulder and spacecraft.	Critical	Modified con-ops where the seismic sensor is preloaded against the boulder, allowing for the selection of larger, more stable boulders.	Moderate

A special focus has been placed on the anchoring and impactor operation and its risks to the overall mission objectives. Finding the target boulder, athe mission operation, and the debris creation event via the impactorare among the highest-impacting risks of DREAM.

Overall, the DREAM risks are based on scientific unknowns about the target area (Deimos) and environment rather than on the technical maturity or development of certain instruments or mission subsystems. Comparability with similar Missions is justified.

Summary and Recommendations for Next Steps

The Deimos Resource Exploration and Anchoring Mission proposes a feasible, novel, and cost-efficient way to analyze Deimos' composition and structure. It utilizes known instruments and a delayed explosive impactor in combination with robotic arms to study the self-created ejecta plume and present a way of anchoring to the Mars moon's surface boulders.

Anchoring and pushing a celestial body's resource knowledge to reserve is critical in future space utilization. This places DREAM between other scientific missions of high worth and high gain. DREAM presents itself as an option for pushing the limits with known and tested technology in untested areas and low-gravity environments.

Recommendations for implementation and funding are well justified, and this paper could be used as a whitepaper for a planned mission to Demos.

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