Resolving the Origin of Deimos: Combining Global and Local Compositional Analysis with the small-sat TASTE Mission

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Abstract - **Understanding the formation of Phobos and Deimos is critical for decoding the history of Mars and the evolution of the outer Solar System. The scientific debate centers on two models: formation via a Martian giant impact or the capture of D-type asteroids. The TASTE - Terrain Analyzer and Sample Tester Explorer mission seeks to resolve the origin of Deimos by providing essential, detailed knowledge. The high-level scientific objectives of TASTE are to determine Deimos's origin by combining global morphology and elemental composition from close orbit with local surface organic and mineralogical composition acquired via a lander. An hyperspectral camera and a miniaturized X-γ-ray spectrometer will characterize the surface's elemental composition from a stable Quasi-Satellite Orbit. Additionally, radio science**

will acquire data on Deimos ’gravity field, providing constraints on its interior structure. The lander will descend to the surface. Once landed, the Surface Sample Analyser will perform detailed chemical analysis. TASTE, currently in Phase B, uses a 16U CubeSat architecture to perform scientific investigation in a deep-space, low-gravity environment. This talk will present the scientific objectives, the critical role of the mission's data in the origin debate, and the required measurement synergy.

Keywords—Martian moon, Deimos, cubesat.

I. ORIGIN HYPOTHESIS

A. *Impact of a large body*

The moons of Mars may have originated from a massive impact event. For Mars to rotate at its present rate, a planetesimal about 0.02 times the planet’s mass must have struck the young planet [1,2]. This body likely impacted Mars at a speed exceeding 7 km/s, enough to vaporise rock and inject substantial material into orbit. If the vaporised debris entered orbit, it would have formed an accretion disk. However, if both the impactor and proto-Mars were already differentiated, the moons formed from the aggregation of disk material would be poor in metals and siderophile elements. Vaporisation caused by the impact, along with the escape of volatile compounds into space, could also explain why the moons are depleted in volatile elements relative to Mars.

Study [3] applied scaling laws and related reasoning to support this impact hypothesis. Under this model, the loss of low-temperature volatiles is expected in both moons because the vaporised ejecta would separate elements based on their volatility. This idea is supported by the absence of a strong hydration signal in the 3 mm band, observed by the Phobos 2 Infrared Spectrometer (ISM), as well as by ground-based telescopic data. Phobos and Deimos are considered the earliest satellites to have formed, with Deimos possibly being the only one formed and preserved beyond synchronous orbit. Their small masses may result from their composition as loosely bound material from the accretion disk. This would also suggest a lack of volatile components, such as water. Their orbital eccentricities and inclinations are difficult to reconcile with capture models but could arise naturally from formation within a circumplanetary disk.

The absence of clear isotopic differences between Mars and its moons indicates that the moons likely inherited their composition from the impactor. Thus, the make-up of Phobos and Deimos may depend more on the large colliding body than on Mars itself, similar to the Earth–Moon system, where most orbiting material is thought to have originated from a Mars-sized impactor rather than the proto-Earth [6].

B. *Captured object*

Dynamical models of the early Solar System indicate that C-, P-, and D-type bodies may have migrated inward from outer regions [7]. Although this scenario has not been fully tested for Phobos and Deimos, some spectral evidence suggests the moons resemble primitive D-type asteroids [8, 9]. These extremely primitive objects are comparable to inactive comets, remnants of the population that delivered volatiles and organic material to the inner planets during their formation, helping establish conditions for life. They may also have gathered and retained debris ejected from Mars during its earliest history, such as the Noachian era. Transfer of simple organisms from Mars to the moons via such debris is a plausible mechanism. If the moons are ultracarbonaceous bodies captured by Mars, they would represent highly valuable targets for robotic exploration.

Observations show that the spectral properties of Phobos and Deimos resemble those of carbonaceous chondrites [10]. These meteorites typically have relatively unfractionated compositions and consist of chondrules embedded in a fine-grained matrix. Isotopic data among different carbonaceous chondrite groups suggest genetic links between them. A key characteristic of CM chondrites is the coexistence of high-temperature anhydrous silicate minerals (like olivine and pyroxene) with low-temperature hydrated clay minerals. These clays are thought to have formed through aqueous alteration of earlier high-temperature phases, either in space or within the parent body. Isotopic analyses can shed light on the connection between asteroids and known meteorites, especially since some CM and CI chondrites have experienced heating sufficient to dehydrate phyllosilicates.

II. SCIENTIFIC OBJECTIVES

To determine the moon's origin, we need to combine global observations from a close orbit with direct surface analysis via a lander. Through this combination of orbital and in situ investigations, the proposed mission will achieve the following scientific objectives:

A. *Global morphology and setting*

The orbiter's primary goal is to conduct a comprehensive global survey and mapping campaign to contextualise subsequent lander observations. The science team will generate high-resolution morphological maps to characterise Deimos's geology and constrain various surface process scenarios. These global maps will inform the selection of landing sites and enable the team to interpret in situ data within a broader geological context.

Deimos's surface terrains are thought to preserve characteristics acquired during the first few hundred million years of the Solar System's existence. Estimating the moon's global elemental abundances would provide valuable information about the early development of Mars, whose own early geological record has largely been erased by billions of years of activity. Furthermore, if the moons formed via a giant impact, mapping variations in elemental abundance could help to elucidate the chemical and physical properties of that formation process.

B. Landing site morphology and texture

Once deployed, the lander will conduct a detailed in-situ study of the local morphology, structure and texture of the regolith and rocks. This includes analysing both rock and small-scale particle size distributions. Microscale textural investigations will be pivotal in understanding the nature of the surface materials and will enable direct comparisons to be made with terrestrial minerals, meteorites and extraterrestrial samples returned by ongoing space missions.

Analysing the organic content of the landing site is vital for investigating the origin and evolution of the Martian moon. In situ extraction and analysis of organic compounds from surface samples will provide unique constraints on formation models. For example, if the two moons are primitive asteroids captured by Mars, then high abundances of organic compounds and volatile elements are expected.

The TASTE mission is designed to achieve these objectives. The TASTE orbiter will be released from a mothership and inserted into Deimos's sphere of influence. After insertion into a close orbit, the TASTE orbiter will then deploy a TASTE lander for in-situ analysis. This approach provides an optimised spacecraft for transfer and orbital operations in terms of size, solar array dimensions and payload configuration. Similarly, the landing spacecraft design is optimised to minimise size and enhance safety during landing, sampling, and near-surface manoeuvres. The lander's surface manoeuvres will be performed via a tilting mechanism, enabling it to analyse samples and use its camera at multiple sites on Deimos's surface.

III. MISSION ANALYSIS

C. Deimos orbit reachability

The total impulse, as well as the ToF required to reach the operational orbit in the Mars-Deimos system starting from an Earth-Centered departure orbit is too high to be faced by a CubeSat. Therefore, it is necessary to consider a launch and an interplanetary transfer shared with another mission and a subsequent transfer to Deimos after that the main carrier perform Martian Orbit Insertion (MOI).

In this scenario, electric propulsion is selected as the main propulsive solution due to the very high total impulses that are needed to complete the transfer from a wide range of possible release orbits. The investigated possibility is to have a release in a Mars bounded orbit after carrier Martian Orbit Insertion. Since the carrier still needs to be identified, a reachability analysis has been performed in order to understand what is the feasible range of orbit release that is compliant with TASTE propulsive capabilities. More in detail, Figure 1 show the total impulse and the time of flight required to reach Deimos orbit starting from a given release orbit, parameterized with respect to the inclination, the eccentricity and the semi-major axis of the release trajectory. The results presented here are valid for a 42 kg spacecraft, equipped with lo thrust electric propulsion. The baseline engine provides a total impulse of 33.4 kNs and 1.1 mN of maximum thrust. It was chosen to select this engine as baseline as the analyses show that a large total impulse is needed to go from the potential release orbits (which often have a high inclination and are far from the trajectory of Deimos). Additionally, the transfer time is constrained as well, to leave sufficient time for the scientific operations around Deimos and for the disposal while still keeping the overall mission lifetime within 3 years. From a mission analysis standpoint this translates into the need to have the highest possible thrust, further justifying the adopted baseline selection against other alternatives on the market, behind as TRL also.

The analysis has been repeated including only a single engine. This is done since including a single propulsion unit would greatly facilitate the configuration of the orbiter, allowing for mass and volume savings at the expense of a loss in terms of available ΔV for the transfer.

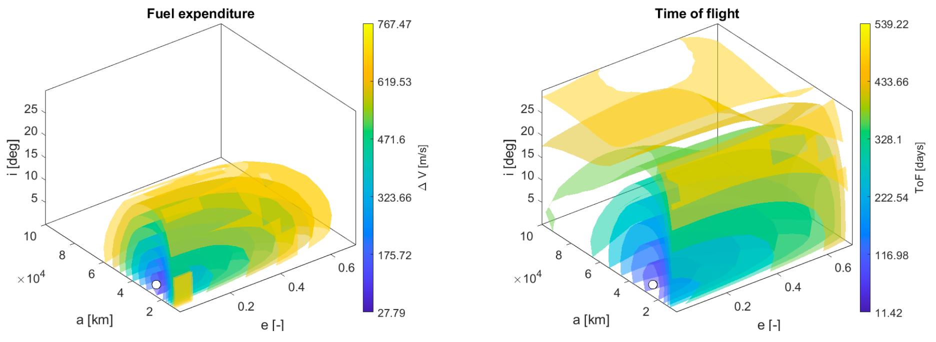

Fig. 1. ΔV (left) and time of flight (right) to reach Deimos depending on release orbital elements. Results are constrained to a maximum total impulse of 33.4 kNs (one Busek BIT-3) and a maximum time of flight of 18 months.

D. Scientific orbit selection

Once the spacecraft arrives at Deimos after completing the transfer, it needs to start orbiting the Martian satellite from a close scientific orbit. Due to the strong gravity pull of Mars and the mass of Deimos being too small to capture a satellite, it is not possible to orbit the Martian moonlet in the usual two-body sense. However, orbits of a special kind, also called Quasi-Satellite Orbits (QSO), exist and can be sufficiently stable to allow operations in the vicinity of Deimos. These have been obtained under the Circular Restricted 3-Body Problem plus Deimos polyhedral gravity assumptions, since the difference between a spherical approximation and the actual gravity field can reach values up to 20% when close to the surface.

In accordance with scientific requirements, two target QSO are identified (see Table I):

1. A large QSO with a distance oscillating from 18 km to 21.5 km from the center of mass of Deimos, called Mapping-1 orbit, serving as a stationing orbit for the "far range" phase.
2. A small QSO called Mapping-2 orbit, with a size of 14 x 15 km, for the higher resolution imaging of the surface, and for releasing the lander to a falling trajectory on the surface of Deimos, as foreseen for the "close-range" phase.

Considering the properties of the baseline multispectral camera proposed on the orbiter, also the ground resolution can be computed. In the far-range phase, a minimum resolution of 0.32 m/pixel is achieved (with maximum peak of 0.53 m/pixel) in PAN imaging mode, while for the close-range phase the best obtainable resolution is of 0.19 m/pixel (with maximum peak of 0.36 m/pixel). All relevant results of these coverage and resolution analyses are reported in Table II,

TABLE I. GEOMETRICAL FEATURES OF THE SELECTED QSO.

	Mapping-1	**Mapping-2**
Orbit period	10.5 hours	7.5 hours
Orbit radius	**Min:** 18 km **Max:** 21.5 km	**Min:** 14 km **Max:** 15 km
Distance from surface	**Min:** 9.5 km **Max:** 17.2 km	**Min:** 5.1 km **Max:** 11.4 km

TABLE II: MAXIMUM ACHIEVABLE COVERAGE, RESOLUTION, AND GROUND VELOCITY THRESHOLDS FOR THE SELECTED QSO.

	Mapping-1	**Mapping-2**
Maximum latitude coverage	80% Achieved in 13 revolutions	74% Achieved in 17 revolutions
Resolution **GSD 16 m/px @ 500 km**	Best: 0.32 m/px Worst: 0.53 m/px	Best: 0.19 m/px Worst: 0.36 m/px
Resolution **GSD 32 m/px @ 500 km**	Best: 0.64 m/px Worst: 1.06 m/px	Best: 0.38 m/px Worst: 0.72 m/px
Projected velocity on ground	Min: 1.4 m/s Max: 3.3 m/s	Min: 2.0 m/s Max: 4.4 m/s

IV. LANDING STRATEGY

Starting from the target mission objectives, three different strategies have been identified for the descent of the lander towards the surface of Deimos. The analyses focused on three different alternatives for the release of a lander to the surface of Deimos to perform in situ scientific observations:

- **CASE 1:** The deployment of the lander from Mapping-2 orbit with a ΔV given by a separation mechanism sufficient to have a safe ballistic descent of the lander itself to Deimos.
- **CASE 2:** a ballistic descent starting at lower altitude with respect to Mapping-2 QSO. In this scenario, the orbiter needs to place itself close enough to the surface for enough time and with proper orientation to allow a safe release of the lander and then to go back to the nominal QSO once a safe settlement on the soil is ensured. A similar strategy was adopted by the Japanese mission Hayabusa-2 for the release of MASCOT lander on the surface of Ryugu.
- **CASE 3:** the release of the lander from Mapping-2 exploiting a miniaturized propulsive system on board the lander itself to achieve a soft landing.

The choice of the nominal baseline plus a backup solution has been consolidated at this stage, after the further refinements in the definition of the scientific orbits. CASE 1 is selected as the baseline landing strategy of TASTE as this reduces all risks related to high autonomy levels at Martian distances, while also allows fitting all other subsystems with enough margin in the orbiter. A chemical propulsive subsystem is included anyway in the orbiter, but a smaller version can be selected, as it will only be used for detumbling, desaturation, and contingency operations. In addition, CASE 2 is kept as an in-flight backup alternative in case of unexpected observations of Deimos composition. In fact, the selection of CASE 2 as backup does not prevent the possibility of mounting a separation mechanism that makes CASE 1 a feasible option.

V. LANDER DESIGN

A. *Tilting mechanism sizing*

The lander is equipped with tilting authority to properly orient the sampling tool after touch down, if needed. It is based on a 1U eccentric mass rotation. A Multibody model has been used to size it and assess its 0,3 Nm torque from 33cm offset of a 62g mass compliance with the surface operations needs. As far as hard soil is considered, the motion highlights a margined value of torque. The mechanism has already been breadboarded and functionally tested in laboratory to drive the detailed design and identify potential criticalities, with good results so far. Fine tuning of the simulation parameters to obtain a sand-like soil will provide possibility to reduce the maximum torque, fine tuning the design parameters of the mechanism.

B. *Lander solar array configuration*

The lander peak power production is of 19.3W. It features four deployable wings of solar panels. Each wing is, in this case, composed of two 1Ux2U panels hinged twice to be folded on each of the 1Ux2U lateral surfaces of the lander. This configuration has been selected because it has the advantage of leaving the top surface completely free from solar cells, allowing the installation of the separation ring. A set of 4 PCB-printed UHF antennae are placed on each of the back surface of the solar wings, to have sky visibility from stowed configuration in each possible landing attitude. The bottom face presents such an antenna as well.

VI. STACKED CONFIGURATION

The configuration of the complete spacecraft stack (orbiter, separation ring, and lander) is shown in Figure II.

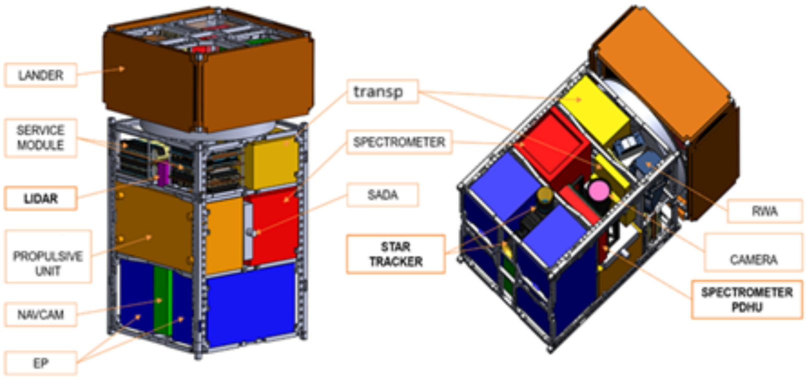

Fig. 2. Spacecraft stack composed of orbiter, separation ring, and lander.

It has been deemed crucial to have the availability of precise altitude measurements during the landing phase. For this purpose, a commercial LIDAR device has been included in the upper tray, exploiting a small gap in between two service module stacks. Finally, the configuration of the star trackers has been optimized to increase sky visibility, avoiding any field of view (FoV) superposition. One of the optics points in the same direction of the thrusting axis of the electric propulsion units.

VII. ORBITER AND LANDER CAMERAS

In order to map Deimos's surface from close observation orbits, a multispectral imager has been mounted on the orbiter. The choice of camera is determined by resolution, swath performance and functional availability. The lander is equipped with a VIS camera to acquire images of the surroundings at the landing site. The choice of camera to be mounted on the lander mainly depends on its size, given that 0.7 U of volume is dedicated to the camera. Two alternatives have been investigated: both options have a 100% success rate in spaceflight, meaning the current readiness level is TRL 9 in LEO; however, neither has previously flown in deep space.

VIII. SURFACE SAMPLE ANALYZER

The TASTE lander is equipped with a Surface Sample Analyser (SSA) that will analyse the chemical composition of the surface. Surface samples will be collected and ingested inside the lander, where soluble organics will be extracted using liquid solvents. A portion of the sample solution will then be delivered to the Lab-on-Chip device for quantitative analysis. The SSA comprises a sampling system; a mixing chamber coupled with reservoirs; a pumping system that delivers the liquid phase to a lab-on-chip detection system via a microfluidic network; a set of sensors at the detection sites; and an ancillary readout board. The SSA is based on two main subsystems: the Sample Acquisition Mechanism (SAM) and the Sample Analytical Laboratory (SAL). The proposed solution is a compact, standalone analyser with an integrated sampling mechanism. It is an end-to-end (E2E) system that minimises sample handling from soil to analysis chamber.

A. Concept of Operations

The ConOps of the SAM are divided into the following phases:

Collection: The sampling system collects solid grains samples from the target body surface and ingests them in the mixing chamber;
Pressurisation: The inert pressuriser is introduced in the chamber, forcing the circular selector to expand on the walls of the shell, sealing the entire chamber.
Discharge: The whole chamber is cleaned with the inert gas, such that it can be reused for the next sample analysis. A multiple sampling of the soil at different locations is envisaged.
The collection system, confined in a 1U, is based on a 7 cm combined coaxial drill-auger conveyor system which has been specifically designed and breadboarded; functional tests, performed in laboratory on representative soil simulant, confirmed the capability to transfer grams of loose material from the moon surface to the mixing chamber inside the lander in less than 1 minute. The drill operates first, to fix the auger tip in the terrain; the conveyor then starts rotating for the material transfer inside the lander. Tests allow fixing the geometrical and operational baseline for the auger conveyor, sensitive to inclination, rotational speed, pitch and clearance, being high rotational speed, low pitches and slight inclination beneficial to support the volumetric flow rate in the auger.

The ConOps of the SAL are divided into the following phases:

Mixing: The samples in the mixing chamber are diluted in liquid phase throughout the use of a solvent coming from reservoirs; Temperature is increased up to maximum 50 °C for 10 min each step. This procedure allows the liquid extraction of soluble organics. The liquid component is injected in the chamber, diluting the solid samples.
Injection: An aliquot of extracted organics in the liquid phase is then injected in a microfluidic network and to detection sites.
Detection: The readout board reads photocurrents from the detection sites of such a solution into the sensitive surface of the Lab-On-Chip.
Extraction: Organic material is extracted from the solid sample using the solvent.
Filtering: Solution is filtered for solid grains and de-bubbled by and intermediate state. Possible cycling to remove all the bubbles and smaller grains if the filtering system is closed on the SEC.
Measurement: The extracted surnatant is passed to SAL. Several channels are available to perform fluorescence experiment with diodes and illuminator.

The core of the SAL consists of the cuvette with integrated microfluidic lines. In this way we avoid tubes. These elements are press-fitted, ensuring a fluidic seal without the need for external connections. To ensure structural integrity and prevent accidental removal of parts, the system uses specially designed inserts and pins that "pack it all in" preventing vibrations from disassembling the system.

The system includes a microvalve to selectively activate the fluidic line of each individual stage. In total, the complete system involves the integration of 5 analytical stages. The whole device is extremely compact, as seen in Figure 3 and several of them can be assembled in an array assembly, where individual UV stages are placed in predefined slots. Control electronics will also be integrated in this configuration.

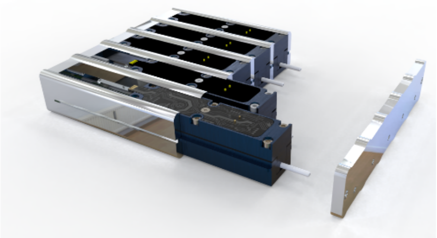

Fig. 3. Array of SAL design.

IX. X-RAY AND GAMMA-RAY SPECTROMETER

TASTE Orbiter will mount a gamma and X-ray spectrometer that inherited from the HERMES CubeSat mission for high-energy astronomical observation [11]. The payload shows the following specifications:

- Mass: < 2 kg
- Size: < 1.5 U
- Power: < 6 W

The detector system is composed of number major blocks, considered as following:

- Silicon Drift Detectors (SDDs) couple with scintillator crystals for detecting X and gamma-ray photons, through the so-called Si-switch design: X-ray photons are directly detected by the SDDs, while gamma-rays interact in scintillator crystals (GAGGs), to be finally read out by the same SDDs.
- Detector Support Structure, mounted on the top of the sensitive plane. This structure is split in an upper and a lower part, with an optical filter in-between.
- A Front-End Electronics (FEE) board, a rigid-flex printed circuit board with a slotted main plate and two side wings, connected to the main part with a flexible flat cable is integrated in the board. Read-out operations are managed by an application-specific, low-noise, low-power integrated circuit (ASIC) called LYRA.

The payload is complemented by a Back-End Electronics (FEE), Power Supply Unit (PSU) and Payload Data Handling Unit (PDHU) boards and the overall mechanical structure.

To satisfy TASTE scientific requirements, the X-ray and gamma-ray spectrometer need some modifications with respect to the original HERMES design:

- Use of longer scintillator crystals, that have to be extended to 25 mm, to guarantee a larger energetic dynamical range up to some MeV;
- Development of new ASICs (LYRA-2), to account for the extended energy range;
- Insertion of a collimator in front of the detectors, that is necessary for reducing the field of view to Deimos surface and excluding spurious photons coming from the sky background.

X. CONCLUSION

The TASTE mission (Terrain Analyser and Sample Tester Explorer) is a strategic and technically innovative response to one of the most enduring questions in planetary science: the origin of the Martian moons. By deploying a 16U CubeSat platform—consisting of a 12U orbiter and a 4U lander—to Deimos, the mission will provide the missing data needed to complement JAXA's MMX exploration of Phobos.

The mission's success relies on a sophisticated dual-stage operational strategy:

Scientific Synergy: Combining global orbital mapping with *in situ* surface analysis to investigate elemental abundances and organic content, testing the "giant impact" versus "asteroid capture" hypotheses.

Technical Innovation: Utilizing specialized Quasi-Satellite Orbits (QSOs) to overcome the gravitational challenges of Deimos, allowing for both stable long-range observation and precise landing-site delivery.

Developmental Maturity: As the mission progresses through Phase B, the focus is on rigorous breadboard testing, hardware refinement, and the consolidation of analytical protocols to ensure a mission-ready baseline for the 2030 launch window.

By addressing the current lack of scientific data on Deimos, TASTE will not only enhance our understanding of the Martian system but also provide broader insights into the evolution of terrestrial planets. The synergy between its high-resolution orbital mapping and direct surface investigations positions TASTE as a vital component of the next decade of international deep-space exploration.

XI. ACKNOWLEDGMENTS

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