Calathus: A sample-return mission to Ceres

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Oriane Gassot
University of Grenoble

Paolo Panicucci
Institut Supérieur de l'Aéronautique et de l'Espace (ISAE)

Giacomo Acciarini
University of Strathclyde

Helena Bates
Natural History Museum, London

Calathus: A Sample-Return Mission to Ceres

Oriane Gassot[a], Paolo Panicucci[b,c,d], Giacomo Acciarini[e], Helena Bates[f,g], Manel Caballero[h], Pamela Cambianica[i], Maciej Dziewiecki[j], Zelia Dionnet[k], Florine Enengl[l], Selina-Barbara Gerig[m], Felix Hessinger[n], Lucy Kissick[g], Moritz Novak[o], Carmine Pellegrino[p], Angèle Pontoni[q], Tânia M. Ribeiro[r], Clemens Riegler[s], Nini Berge[t], Nikolaus Huber[u], Richard Hynek[v], Bartosz Kędziora[w], Adam Kiss[x], Maurice Martin[y], Javier Navarro Montilla[z]

[a]*Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France*
[b]*CNES, 18 Avenue Edouard Belin, 31400, Toulouse, France*
[c]*ISAE-SUPAERO, 10 Avenue Edouard Belin, 31400, Toulouse, France*
[d]*Airbus Defence & Space, 31 Rue des Cosmonautes, 31400 Toulouse, France*
[e]*University of Strathclyde*
[f]*Natural History Museum, London*
[g]*University of Oxford*
[h]*Universitat Politècnica de Catalunya*
[i]*INAF - Astronomical observatory of Padova, Vicolo dell'Osservatorio 5, 35122 Padova, Italy*
[j]*Wroclaw University of Science and Technology*
[k]*Università degli studi di Napoli Parthenope*
[l]*KTH Royal Institute of Technology*
[m]*Physikalisches Institut, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland*
[n]*Luleå University of Technology*
[o]*Vienna University of Technology*
[p]*Techincal University of Munich, Institute for Nanoelectronics, 80333 Munich, Germany*
[q]*Swedish Institute of Space Physics, Kiruna, Sweden*
[r]*IFIMUP and Departamento de Física e Astronomia, Faculdade de Ciências da Universidade do Porto, Rua do Campo Alegre 687, 4169-007 Porto, Portugal*
[s]*JMU Würzburg*
[t]*Laboratoire de Physique et de Chimie de l'Environnement et de l'Espace, University of Orleans, CNRS*
[u]*Uppsala University*
[v]*University of West Bohemia*
[w]*Warsaw University of Technology*
[x]*Budapest University of Technology and Economics*
[y]*University of Stuttgart*
[z]*Institut National des Sciences Appliquées*

Abstract

Ceres, as revealed by NASA's Dawn spacecraft, is an ancient, crater-saturated body dominated by low-albedo clays. Yet, localised sites display a bright, carbonate mineralogy that may be as young as 2 Myr. The largest of these bright regions (faculae) are found in the 92 km Occator Crater, and would have formed by the eruption of alkaline brines from a subsurface reservoir of fluids. The internal structure and surface chemistry suggest that Ceres is an extant host for a number of the known prerequisites for terrestrial biota, and as such, represents an accessible insight into a potentially habitable 'ocean world'. In this paper, the case and the means for a return mission to Ceres are outlined, presenting the Calathus mission to return to Earth a sample of the Occator Crater faculae for high-precision laboratory analyses. Calathus consists of an orbiter and a lander with an ascent module: the orbiter is equipped with a high-resolution camera, a thermal imager, and a radar; the lander contains a sampling arm, a camera, and an on-board gas chromatograph mass spectrometer; and the ascent module contains vessels for four cerean samples, collectively amounting to a maximum 40 g. Upon return to Earth, the samples would be characterised via high-precision analyses to understand the salt and organic composition of the Occator faculae, and from there to assess both the habitability and the evolution of a relict ocean world from the dawn of the Solar System.

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1. Introduction

The concept of a star's habitable zone — a region of astrobiologically favourable warmth — has commensurately weakened with the growing understanding of the so-called *ocean worlds*. These are Solar System bodies that potentially contain sub-surface reservoirs of liquid water, whether global or local, definite or speculative [1]. Europa and Enceladus are the founding archetypes of this category [2, 3], but it is now understood that these encompass a much wider collection of Solar System bodies than first thought. From the Sun outward, Ceres, Ganymede, Callisto, Titan, Triton, Pluto, and Charon may host or have hosted subsurface liquid reservoirs [4, 5, 6], while additional outer worlds including Oberon, Titania, and Eris are a source of speculation [7]. Of these, geologically-recent activity is either observed or inferred for Europa, Enceladus, Triton, Ceres and Pluto, and of these, all bear extrusions of their subsurface hydrosphere readily accessible upon their surface. Cryovolcanism has been widely conjectured in some form of Saturn's moon, Titan [8], and the Titan's thick atmosphere is considered as a strong argument in favor of recent activity [9], but the interpretation of Cassini data has been insufficient to demonstrate conclusively whether Titan is, or even has been, cryovolcanically active [9].

Ocean worlds are a focal point of interest in planetary science for presenting a convergence of the fundamental requirements for known life: a source of energy, a liquid solvent, and the resulting chemical gradients for mobilising biologically relevant elements including C, H, N, O, P, and S. All the active-to-dormant ocean worlds discussed above show evidence of the other known prerequisite for life, which is complex organics [10, 11, 12, 13, 14].

In this context, studying Ceres may solve remaining inquiries concerning the formation and evolution of planetary systems, and particularly the main belt. Based on the data from the Dawn mission, the surface of Ceres is consistent with aqueous alteration of CM chondrites [15], suggesting first that the largest object of the main belt could be a carbonaceous body, different from the non-carbonaceous body formed in the inner solar system [16], but also that that Ceres experienced global aqueous alteration. Dawn revealed Ceres as a volatile-rich body, with a partially differentiated interior, which experienced both cryovolcanism and geothermal activity in its recent history. Dawn revealed an ubiquitous presence of hydrated minerals, a distribution of ammoniated phyllosilicates [17, 18] linked to its formation, and a latitudinal variation of abundance of water ice [19] related to the evolution of its subsurface. The presence of subsurface volatiles can be inferred from many geomorphological features : the bright regions within the Occator crater are one of the most remarkable features observed by Dawn, and are the most direct evidence of recent geothermal activity on this body. Being an accessible potential ocean world, a sample return mission to Ceres is fundamental to investigate the astrobiological significance of this body and its subsurface, being a potential favorable environment to prebiotic chemistry in a aqueous environment. [13] .

In addition, sampling an accessible, possibly active, and under Class V protection (classification according to [20] and discussed in the section 4.6) ocean world would further our understanding of this growing class of ocean bodies and could be a forerunner in the development on future landing missions on different likely candidates for hosting extant life in the Solar System.

Here the Calathus mission concept [21, 22] is presented as it has been improved during the Post Alpbach Summer School Event held at the ESA Academy in Redu in 2018. Its aim is to return a sample from Ceres and characterise an ocean world with the full analytical capabilities in Earth-based laboratories. The mission concept is named after the basket which was carried from Ceres, the goddess of harvests, as symbol of abundance and fertility in the symbolic ancient Greek art.

1.1. Dawn's Ceres

Ceres, discovered by Giuseppe Piazzi in 1801 [18], holds a unique position among the small bodies of the Solar Systems. Ceres is the most massive body of the main asteroid belt, making up to the 30% of the entire belt's mass [23]. Its observation with Hubble Space Telescope revealed a complex scenario: more a proto-planet than an asteroid, with high-albedo features localized on the surface, and a low density body with stratified mantles and a silicate core [24, 25]. Because of these reasons, on 6 of March 2015, NASA's Dawn spacecraft [26] became the first human-made object to enter in orbit around Ceres, where it began investigations that lasted 3.5 years.

Shape and gravity measurements carried out by the Dawn spacecraft have been used to provide an estimation of Ceres' moment of inertia, which was in turn used to infer its internal structure and evolution, namely by determining its bulk density and rotation poles. The gravity data showed a celestial body with a mean crustal thickness between 27 and 43 km and a surface density between 1200 and 1600 kg/m^3 [27] which implies high water content [28]. Furthermore,

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Dawn revealed a frigid (~160 K [29]), thoroughly cratered, extremely low albedo surface (0.09 [30]) with intermittent bright patches (named *faculae*) often within craters. This predominantly dark surface is comprised of hydroxylated material including ubiquitous Mg- and NH_4-bearing phyllosilicates and Mg-Ca carbonates [17, 18] alongside possible organic molecules [13] that bear similarity to carbonaceous chondrites, particularly the CI- and CM-types [31, 32, 33]. This is consistent with a water-rich, partially-differentiated, carbonaceous and siliceous body.

Craters are Ceres' most prevalent geomorphological feature. These are frequently fractured across their floors and, alongside kilometre-scale fractures not associated with impacts, may represent subsurface pressure rise associated with cryo-magmatic intrusion [34]. A 4 km-high dome named Ahuna Mons is a candidate cryo-volcano formed by the extrusion of such cryo-magma [35]. Unlike most of Ceres' ancient, cratered terrain, the flanks of Ahuna Mons are bright and relatively young — last resurfaced 210 ± 30 Ma [35] — with a spectral signature corresponding to Mg-Ca- and Na-carbonates [36]. This is surprising in the context of Ceres' both minor solar insolation (at 2.8 AU) and diameter (at ~940 km), neither of which are sufficient to explain such geologically recent activity.

The most extraordinary indicator of a recently active subsurface, however, are the bright patches [4], or faculae. These features are defined as bright regions related to past or current outgassing [37], volcanism or resurfacing phenomena. These faculae are of an albedo five to ten times higher than the average cerean surface [38] and, in contrast to the phyllosilicate-dominated crust, are composed predominantly of anhydrous Na-carbonate (Na_2CO_3), with minor hydrated Na-carbonate, Al-phyllosilicates, and NH_4-chlorides [39, 40, 38].

The largest of these exposures are within Occator Crater, in Figure 1. They are unique in both age — at their youngest estimate <2 Ma [41] — but also for their extent: together they cover over 200 km^2 [39], making them the largest of their kind on Ceres, and one of the largest extraterrestrial carbonate deposits in the Solar System.

Occator Crater is 92 km in diameter, centred at 19.9 °N, 239.1 °E, and at maximum 4 km below the surrounding terrain [42]. While relatively flat-floored, the crater is pierced by a prominent central peak 2 km wide and 0.4 km high within a pit 9 km across and 1 km deep [42]. The crater's defining attributes are the faculae: these are Cerealia Facula, associated with the central pit/dome, and Vinalia Facula, which comprises several distinct, discontinuously spread faculae eastward of Cerealia towards the crater rim. The carbonates found in the faculae in Occator, in particular natrite (Na_2CO_3), are different from the Mg-Ca carbonate detected in the global Ceres spectrum [40]. Occator therefore represents the clearest insight into a process that was once widespread, perhaps planet-wide; a process that provides a window into both the ancient and the present cerean subsurface.

With a draping morphology upon the floor of Occator, and an association with both doming and fracturing, the source of these bright carbonates is attributed to cryo-volcanic eruption as fountains of salt-rich water [39, 43]. Their salt-carbonate composition is consistent with the solid residue expected from alkaline brines formed by carbonaceous chondrite interaction with warm fluids: upon exiting the subsurface, the water component of such fluids instantly sublimes in the near-vacuum, leaving the solutes to rain back in the diffuse pattern observed by Dawn.

The source of these fluids beneath Occator is likely a shallow subsurface reservoir: planetary evolution models suggest an ocean may have once existed at shallow depths [44], which may persevere today as localised brine reservoirs. The detection of salt compounds on Ceres' bright spots (Na_2CO_3, NH_4Cl or NH_4HCO_3) may be solid residues from the crystallization of brines that reached the surface from the interior ocean [39]. In addition, laboratory experiments support the outcome of this scenario [45], suggesting also that the detection NH_4Cl on Ceres' surface could imply that the ocean is rich in ammonium and/or chloride.

1.2. The case for a return to Ceres

The faculae of Occator Crater are the exposed interior of a water-rich body [43]. As water is one of the known prerequisites for biota as it is known on Earth, investigating the faculae gives an opportunity to investigate a potential habitable niche and may help our understanding of the variety of potential habitats in our Solar System. Ceres is the most readily accessible of the aforementioned *ocean worlds* to Earth, both as the closest but as one already thoroughly characterised by Dawn. A return to Ceres with the explicit intent to study Occator Crater is to stand upon the shoulders of Dawn to see further still into the workings of a potentially habitable body [4].

A second clear case for the return to Ceres looks not to Ceres' present but to life origins. Ceres' spectral signature does not match any known meteorite clan, which is unusual given both its large mass and the strong connection between certain meteorites and similarly-sized planetesimals (e.g., the Howardite-Eucrite-Diogenite clan and Vesta [46]). Ceres is carbonaceous and most closely aligned to CI- and CM-type chondrites, which are strongly aqueously altered and

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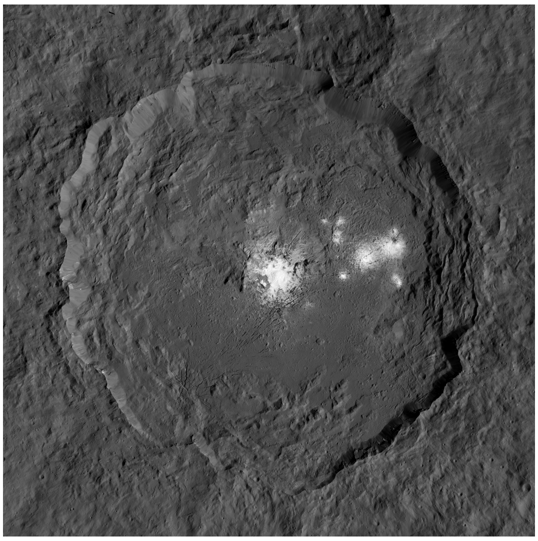

Figure 1: A close-up view of the Occator Crater with its faculae as imaged by the Dawn mission (NASA). The crater is 92 km across (Credits: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA/PSI)

contain a significant organic component. This is of interest for two primary reasons. Firstly, during planetary accretion it has been hypothesised that volatiles and organics were delivered to Earth by carbonaceous chondrites (e.g Alexander et al. [47]) which subsequently enabled the rise of life. Recent missions to similarly volatile- and organic-rich bodies such as the comet 67P/Churyumov-Gerasimenko by ESA's Rosetta-Philae have complicated the subject by suggesting comets were not a major deliverer of these materials [48]. Moreover, the probes of Hayabusa2 (JAXA) and OSIRIS-REx (NASA) will return samples of carbonaceous asteroids within the next years which will provide new data. As the largest-known carbonaceous body, further characterisation of Ceres could develop our understanding of where this body fits in using both meteoritics and returned JAXA/NASA samples, and whether Ceres-class objects were involved in the seeding of proto-Earth with the components that eventually gave rise to life.

Ceres' carbonaceous nature is also of interest because its high volatile content is unusual for its present location. Ceres' high ammonia content could not have condensed within the Asteroid Belt during planetary accretion because ammonia is a vapour at expected temperatures during this time [49]. This suggests either Ceres' ammonia and other volatiles were delivered later or that Ceres itself formed in the outer Solar System before migrating inwards [50]. A return mission to Ceres could resolve such uncertainties by producing high-precision observations that may further or preclude particular hypotheses.

Taken together, the habitability case for the return to Ceres calls for analysis of both the faculae salts and the more widespread organics, while the potential role that planetesimals coming from the same reservoir as Ceres had in providing Earth with life building-blocks may best be studied with a sample of the organics present in the surface rocky material.

1.3. The case for Calathus

In discovering the faculae and linking Ceres with the wider Solar System, Dawn created as many questions as it answered. These can be broadly divided into two main categories of interest:

1. Ceres' spectral features do not match any known meteorite groups, nor can the location of its formation be pinpointed to a specific region. The question remains as to where and how Ceres formed, and whether asteroids of similar composition played any role in the delivery of water/organics to proto-Earth.
2. Ceres appears to contain three of the prerequisites for life: sources of water, carbon, and energy. Ice-rich bodies like Ceres could represent a widespread, astrobiologically-favourable niche.

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To understand the composition and evolution of Occator is to understand the inner workings what has been called a relict — potentially extant — ocean world [51], providing a snap-shot inside not only Ceres but a whole class of ice-rich bodies. To this end, it is proposed a return mission to Ceres to sample material from Occator Crater. This would provide invaluable insight into both of these overarching questions, the former of which is in particular an ESA Cosmic Vision priority, as well as to further the study of a world fascinating in its own right.

1.4. Previous and upcoming missions

The Calathus mission to Ceres stands on the shoulders of half a century of in situ and sample return missions:

- The Dawn mission [26] could be considered a precursor or scout mission for Calathus, and provided numerous pieces of evidence supporting the presence of a subsurface cryosphere, as expounded in subsection 1.1. Returning samples from the faculae salts should help determine its nature and composition.
- The Cassini mission [52] during its flight through the plumes of Enceladus confirmed the existence of water beneath an icy surface. Cassini's data could be compared with Calathus' in order to better constrain the conditions of appearance of subsurface oceans on icy bodies.
- The Jupiter Icy Moon Explorer (JUICE) mission [53] to the Jovian system will be orbiting the Galilean satellites by the time Calathus is launched. JUICE will investigate Europa, Callisto and Ganymede, which show strong evidence for harbouring subsurface water oceans, which is one of the setting for extra-terrestrial life of the icy worlds. Calathus and JUICE's results could be treated together to provide knowledge to the appearance of the conditions of life on the solar system icy bodies.
- The Exo-Mars mission [54], which will be launched in 2022, aims at studying the biosignatures of past Martian life. ExoMars and Calathus scientific return could both be handled to answer the question of the appearance of life in various location in the solar system.
- Finally, there are multiple lessons to be learnt from the technological aspects of missions hosting landers. The Rosetta mission with its lander Philae [55] reached the comet 67P/Churyumov-Gerasimenko in 2014, with the prime objectives of investigating the origin of comets. Rosetta serves as a source of both scientific and technological inspiration. Philae lander successfully deployed and operated even under adverse circumstances of harpoon failure on the comet nucleus and thus can be used as a starting point to develop a Ceres lander, by reinforcing the landing system design where it failed. The lander's designs are also inspired from missions such as InSight [56] and upcoming Luna-27 [57].

2. Science Case

Based on the open questions left by the Dawn mission, Calathus is proposing a further exploration of Ceres with a detail that only a sample return mission can offer. Returning pristine material from Ceres, particularly from the Occator Crater, and studying it on Earth would provide new insights into fundamental questions related to the origin and evolution of Ceres and its astrobiological potential. Thus the driving questions addressed by Calathus are broadly divided into those two categories:

1. Ceres' origin and its evolution in the Solar System
2. Ceres astrobiological potential

The Calathus' scientific questions and the corresponding objectives are described in detail below and summarized in Table 1 .

2.1. Category 1: Ceres' origin and its evolution in the Solar System

Ceres' spectral features do not match any known meteorite groups, nor can the location of its formation be pinpointed to a specific region, leaving the question on where and how Ceres formed open. In this context Calathus would address the following questions:

1.a *What is the nature of Ceres' carbonaceous material?*
The physicochemical, mineralogical, and morphological analysis, in situ and on-Earth, of the carbonaceous material on the Ceres' surface would provide information about its pressure and temperature of formation. This would constrain the origin of Ceres in the Solar System.

1.b *Where did Ceres and other spectrally dark type asteroids form?*
Determining the composition of surface material at Ceres would give an insight into Solar System evolution and reorganization after Jupiter formation. This would constrain the early migration scenario of giant planets in the Solar System.

1.c *What is the nature of the bright material at the Occator's faculae?*
The exact composition of the bright spots material is unknown as Dawn's VIR instrument has a limited spectral range (1-5 μm). Earth-based analysis are crucial to discretize the chemical species and assess the subsurface reservoirs composition.

2.2. Category 2: Astrobiology at Ceres

Dawn data revealed the presence of water and localized complex organic molecules on the cerean surface. Both are essential ingredients for life as it is known on Earth. Whether these organic molecules are original from Ceres or an exogenous delivery is still to be determined. It is of importance to understand and characterize these organics, to evaluate the past and present astrobiological potential of Ceres. In this context Calathus would address three main questions:

2.a *Were – or are – the ingredients for life present in the subsurface of Ceres?*
The Occator crater is an almost unique place in the Solar System where to easily access and sample pristine material from subsurface reservoir. By orbital, in-situ and on-Earth characterization of the faculae's material, the chemical and organic composition of the primordial subsurface reservoir can be investigated.

2.b *What role do cryospheres play in the search for life?*
The presence of subsurface oceans in other bodies of the Solar System has questioned the concept of habitability zone as it has been defined. Additionally, the presence on Earth of active deep ocean vents has questioned the importance of light as a primary source of energy. Therefore, the investigation of the Ceres' cryosphere, even if no longer active, is an important milestone to study active and relict ocean worlds. The cryovolcanism could offer a means to expose organics (if present) to water, through the motion of the brine that could promote the transfer of material from the surface to the subsurface [4] and create flows, fissures, and cracks deep enough for significant interaction to occur over time. This could promote the formation of more evolved organic species.

2.c *Did the main belt asteroids spectrally similar to Ceres contribute to the delivery of Earth's water?*
The question of the origin of water on Earth has been discussed mainly based on the deuterium-to-hydrogen ratio (D/H). In-situ characterization of Ceres hydrogen, oxygen, and nitrogen stable isotopic ratios would provide additional information about the delivery of water to the Earth, allowing to different proposed scenarios to be distinguished [58].

2.3. In-situ measurements

In order to address all scientific objectives as well to reduce the complexity of the overall mission, in-situ measurements would be performed, primarily pertaining to the potentially volatile substances. These measurements would ensure that all objectives of the mission can be achieved regardless of alteration of the volatiles during the return phase: thus, no active thermal control would be required for the sample and re-entry capsules.
The gas chromatography mass spectrometer would analyse in situ the D/H ratio as well as the oxygen and nitrogen

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Table 1: Science questions addressed by Calathus

	Science question	Science objective
Ceres Origin and Evolution	What is the nature of Ceres' carbonaceous material?	Investigate the chemical composition of the carbonaceous material.
		Explore the mineralogy and morphology of the carbonate grains.
	Where did Ceres and other spectrally dark type asteroids form?	Map the surface of Ceres.
		Estimate the elemental abundance and isotopic composition (e.g. stable isotopes of oxygen and chromium)
		Estimate the volatile content.
	What is the nature of the bright material at the Occator's faculae?	Identify the mineral composition.
		Map the mineral distribution.
		Investigate under what conditions the faculae formed.
Astrobiology at Ceres	Are the ingredients for life present in the Occator Crater?	Search for the presence of prebiotic and biologically-relevant organic molecules.
		Characterise the organic material if present.
	What role do cryospheres play in the search for life?	Investigate the physicochemical composition of the subsurface reservoir.
		Search for biosignatures.
	Did main belt asteroids spectrally similar to Ceres contribute to the delivery of Earth's water?	Measure hydrogen, oxygen and nitrogen isotopic variations and relative abundances of volatiles on the cerean surface.

stable isotopic ratios of one collected sample, characterise the different isotopic ratios of any volatiles and the relative abundances of gases exposed during the drilling of the samples. In addition, a detailed mapping of the landing and sampling sites would be performed, creating topographic maps for an initial characterisation. A thermal infrared mapper would measure temperature variation of the surface and a surface penetrating radar would be used for selection of the landing site and analysis of Ceres' geological features.

2.4. Sample analysis on Earth

In order to fulfil the Calathus' scientific objectives, the following sample analyses are required:

1. X-ray diffraction (XRD) for determining the mineral or chemical structure of the sample.
2. Gas-chromatography mass-spectroscopy (GC-MS) for the identification of the insoluble organic phase.
3. X-ray absorption near-edge structure (XANES) for identifying spatial distributions of organics and minerals and the link between them.
4. Electron microprobe for analysing the elemental composition.
5. Scanning electron microscopy (SEM) for determining the sample microstructure.
6. Thermal ionization mass spectrometry (TIMS) for calculating the age of the components, by calculating ratios of radioactive isotopes.

All mentioned methods require large, massive and extremely high precision instrumentation, which is not feasible to accommodate on a spacecraft. Thus these measurements would be carried out on the samples after their retrieval on Earth. Additionally, a percentage of the samples would be stored and would provide material for future generations of scientists to use methods and techniques not yet invented.

The main priority of the sample return is the retrieval of the white carbonate material from the Occator faculae. As dark coloured organic matter is ubiquitous on the surface [59], it is highly likely that it would also be present at the landing site. In the unlikely case of the sample containing exclusively white material, the majority of the scientific questions could be answered.

3. Mission requirements

A system engineering approach has been used by employing the concurrent design software Open Concurrent Design Tool (OCDT) from ESA [60] which leads to a Phase 0 study of a sample return mission to Occator crater. Requirements have been identified at system and subsystem level but, for the sake of brevity, only system driving requirements are listed in this section. The driving requirements are:

1. The mission shall perform a sample return of at least a total of 4 cm^3 of bright material from Ceres to ensure there is enough mass to perform the minimum necessary analysis on Earth.
2. The sampling mechanisms shall be capable of removing the upper 5 mm of the surface and sampling from below this depth so as to avoid to sample material from the the near subsurface which may be contaminated by space-weathering [61].
3. Contamination of the surface of Ceres shall be limited to 180 ng/cm^2 of hydrazine during descent as in the OSIRIS-REx mission [62]
4. Four samples of 4 cm^3 shall be collected and returned to Earth in order to maximise the amount of analysis that can be performed on Earth.
5. At least one additional sample shall be collected and analysed in-situ.
6. The lander shall be able to cope with boulders and surface features up to diameter 0.6 m. This requirement is driven by the small lander size.
7. The Calathus system shall support the selection of sampling locations based on visual inspection.
8. The samples shall not be contaminated with terrestrial material or organics.
9. The conditions in the interior of the sample capsule shall be monitored during return phase, re-entry and collection. It must be noticed that in this paper the design of the re-entry capsule itself is not addressed. Thus, the monitoring system inside the capsule is not expounded.
10. The orbiter should characterise Ceres surface with a resolution of 1.1 px/m to identify the correct landing site and to provide scientific and contextual information for the sample analysis

These requirements influence what are considered to be the most critical part of the design: the sampling operation (items 1, 2, 5 and 7), the sampling mechanism (items 2, 4, 5 and 7), the lander descent (items 3 and 6), the planetary protection (items 3, 8 and 9), and the landing site selection (item 10).

4. Mission profile

The goal of Calathus mission is to return a sample from Ceres. The spacecraft Calathus consists of four segments: the orbiter, the sample canister, the propulsion platform and the surface module. The latter three parts comprise the lander Piazzi.

The mission phases are summarised in Figure 2 and detailed in the following sections.

4.1. Launch requirements

The Calathus mission would begin with a launch from Kourou, French Guiana, using the Ariane 64 rocket. The spacecraft's wet mass at launch is 5780 kg, and the dimensions (see Table 5 at the end of the article) allows for a dual launch configuration. The targeted ΔV is 10.6 km/s in the Earth inertial frame, which allows for a good start on the trajectory to Ceres.

4.2. Interplanetary Trajectory

Two different interplanetary orbits had to be defined for this mission. The initial connects the Earth to Ceres: this trajectory was designed using low-thrust propulsion and also leveraging a flyby to Mars for gravity assist. Since this is a sample return mission, the return trajectory is also optimized and analyzed using an analytic-based method. For the return case, a relatively high infinite velocity at the Earth is allowed, since most of the remaining energy can be dissipated in the Earth's atmosphere during the re-entry trajectory.

The outbound orbit is found by optimizing the whole trajectory in a global optimization framework. Specifically, a local optimizer of the ESA's global optimization toolbox PaGMO was used [63, 64]. This has allowed an orbit that

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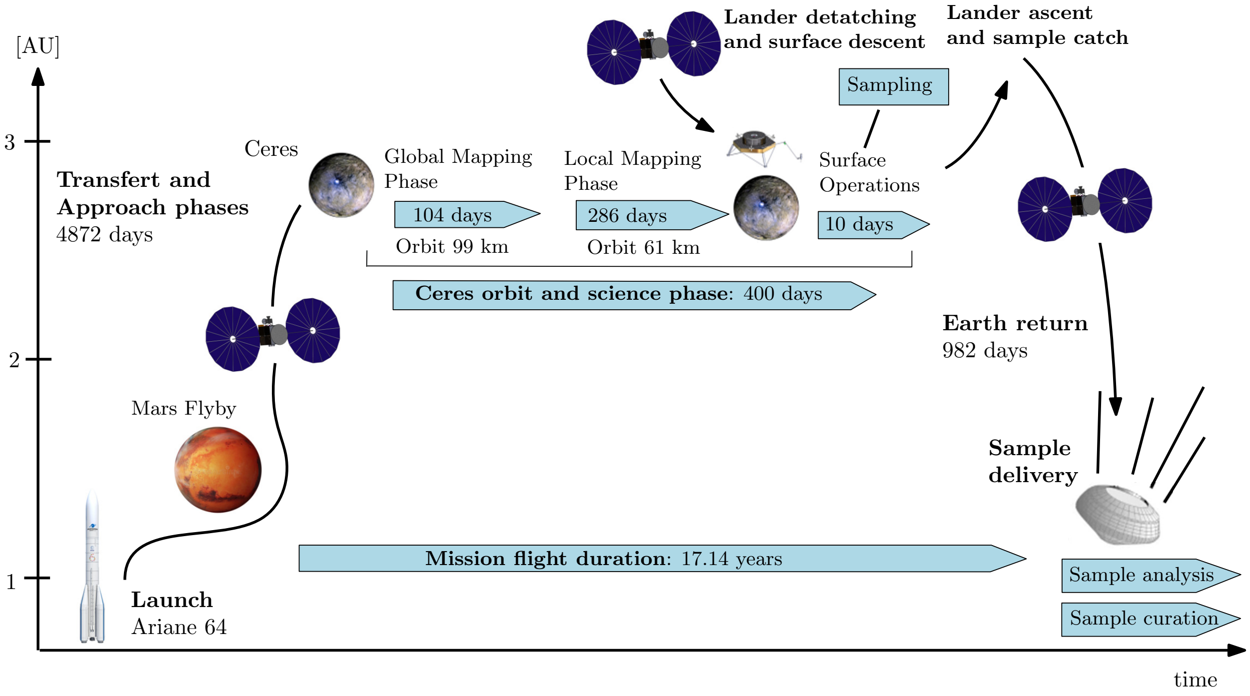


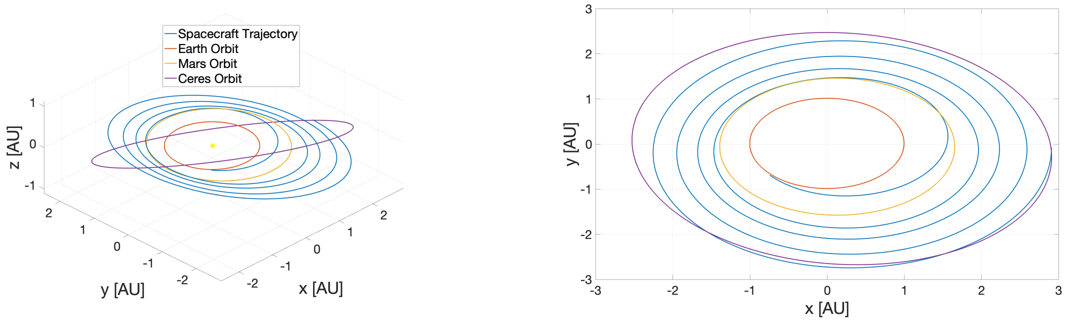
Figure 2: Visualisation of the mission phases of Calathus.

possibly minimizes the propellant consumption to be found, while still fulfilling the mission and system requirements. This orbit has a departing date: of the 29th of April 2031. After four revolutions around the Sun and a journey that lasts nearly 4872 days, the spacecraft then reaches Ceres on the 30th of August 2044. In Figure 3 the three-dimensional trajectory in the Sun-centered ecliptic reference frame and its two-dimensional projections are shown. During its journey, the spacecraft performs a flyby of Mars (for which it was designed and optimized), gaining a change in velocity (ΔV) of 2.7 km/s. Also, the orbit shows a spiral-like shape that is typical for low-thrust orbits.

For the inbound trajectory, an analytical representation of low-thrust trajectory has been employed, which has allowed an inbound trajectory with a low time of flight, a feasible thrust profile and re-entry velocity, and a reasonable infinite velocity at Ceres to be executed. The implemented technique for finding such a orbit consists of a shape-based method to first derive an analytical formulation of the trajectory: from the analytical expression of the trajectory, quantities (such as acceleration, velocity, thrust, mass consumption, etc.) can then be derived to investigate the feasibility and quality of such orbit. The shape-based exponential sinusoid method was used in this paper [65, 66, 67]. The trajectory resulting from this analysis is presented in Figure 4. As shown, the spacecraft reaches the Earth from Ceres (after having studied the dwarf planet's surface for 400 days) in only one revolution. In particular, the time of flight of this trajectory is 2.69 years: this means that the spacecraft would leave Ceres on the 4th of October 2045 and it would reach the Earth on the 11th of June 2048. The spacecraft arrives at Earth with an infinite velocity of $v_\infty = 5.4$ km/s, which allows a re-entry velocity (at 120 km altitude with respect to the Earth surface) of 12.3 km/s. The required initial ΔV at Ceres for the spacecraft to be injected in such a orbit (i.e., for reaching the required escape velocity at Ceres) is 0.4 km/s. It is important to highlight that the 10 Earth days time window for surface operations at Ceres does not take into account anomaly procedures. In future studies, if a new timeline is set-up, it might be needed to iterate on the design of the inbound trajectory.

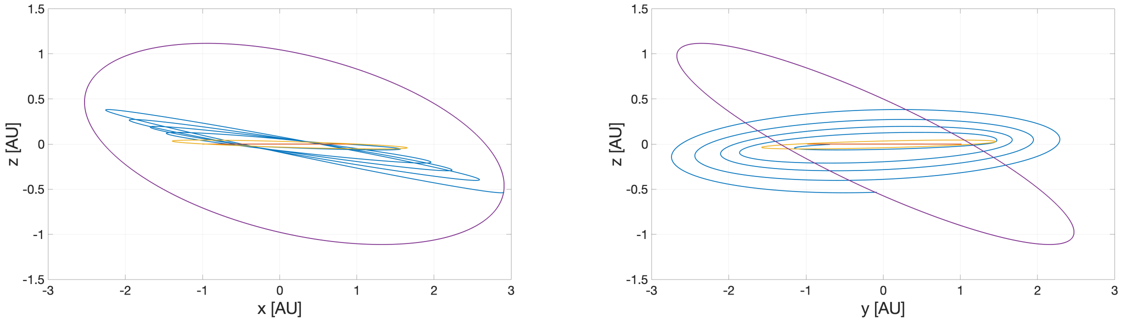
4.3. Trajectory at Ceres

The trajectory at Ceres aims at fulfilling the previously-mentioned scientific and mission requirements by choosing the correct orbit for the spacecraft. For the sake of this study, in this preliminary design all orbits are considered circular and the gravity field of Ceres considers only the term J_2 [27], i.e. the flattening, in order to consider the procession of the ascending node of the orbit. All orbital operations around Ceres are performed with chemical propulsion. This



(a) Spacecraft-Ceres outbound orbit.

(b) Projection of the orbit onto the (X,Y) plane.



(c) Projection of the orbit onto the (X,Z) plane.

(d) Projection of the orbit onto the (Y,Z) plane.

Figure 3: Spacecraft trajectory and its projections in the (X,Y,Z) ecliptic reference system centred in the Sun's barycenter.

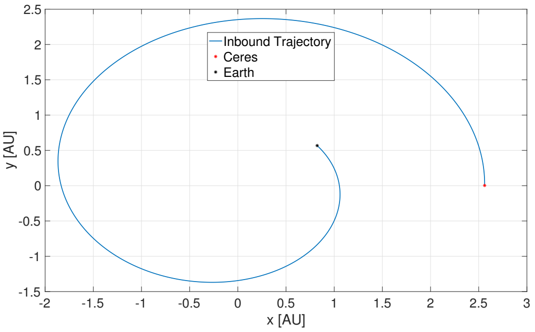


Figure 4: Inbound trajectory expressed in a plane that has the x-axis collinear to the starting position of Ceres and centered in the Sun.

has several advantages: it reduces costs related with xenon; it improves the gravity field determination strategy as longer arc without firing can be exploited; and it reduces the complexity in the orbit determination process. The operations at Ceres are separated into four different phases that correspond to different operational altitudes - given with respect to the reference Digital Terrain Model (DTM) spheroid radius (470 km) - and inclinations:

1. The insertion procedure on the highest orbit around Ceres from the interplanetary trajectory. It is assumed that the B-plane has been correctly targeted during approach thanks to trajectory correction manoeuvres. The targeted orbit, labelled High-Altitude Mapping Orbit (HAMO), is at an altitude of 99.08 km with respect to the surface and an inclination of 95°. The altitude has been chosen to ensure that the camera resolution fulfils the requirement of 1.1 m/px for the global mapping and to complete, thanks to J_2-induced precession of the node, 662 orbits in 221 Ceres days, i.e. 83.5 Earth days, among which 22 cover the Occator crater. To allow

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the transmission of the collected data and to ensure a better global coverage, as the other spherical harmonics coefficients that have not been considered could perturb the orbit, 20 days are added to this phase of the mission. The total duration is 104 Earth days. The ΔV necessary to perform the insertion is 167 m s^{-1} and considers the circularization of the interplanetary orbit and a back-up change of plane of 10° if the B-plane is not targeted correctly.

2. The local mapping of the crater to characterise the possible landing sites and the detailed geomorphology of Occator's crater. The orbit, labelled Low-Altitude Mapping Orbit (LAMO), is at an altitude of 61.25 km with an inclination of 95°. Lower orbits have been considered too affected for higher terms of the gravity field to be operational. The inclination is chosen to minimise the propellant used to pass from HAMO lo LAMO. This orbit allows a resolution of 0.6 m/px. By considering that 0.6-m boulders are detectable with a resolution of 0.3 m/px, only boulder of diameter of 1.2 m can be detected. Boulders smaller than 1.2 m are detected during descent by the autonomous hazardous detection and avoidance system. Smaller hazards would be avoided and managed by the active and controlled descent of the lander as a closest orbit would be perturbed too much by the gravity field. Similarly to the HAMO, the LAMO is chosen because of the precession of the node that allow Ceres to be mapped with the previously-mentioned precision in 1211 orbits in 365 Ceres days, i.e. 138 Earth's days. In order to use the whole scientific suite, the precession is done twice with some margin and this operational phase of the mission lasts 286 Earth's days in order to ensure correct data storage and communication. During this phase about 80 orbits are flown above the Occator Crater, while others are flown to map and characterise other interesting sites, as the Ernutet crater, with a lower resolution than the Dawn mission. The ΔV to move from the HAMO to LAMO, including the inclination change, is 69.50 m s^{-1}.
3. The release of the lander is performed at an altitude of 20 km over the chosen landing site, i.e. Occator crater. The required ΔV is estimated to be 13.84 m s^{-1}.
4. The orbiter then increases its altitude to 109.16 km and changes its inclination to 150° in order to put itself on the Surface Operation Orbit (SOO) where two slots of communication are available each Ceres day. The ΔV required for the change of plane and to reach the SOO altitude from the lander release altitude is 28.48 m/s. Each slot of communication lasts about 30 minutes long which assures the lander operations would be planned and executed on time.

4.4. Descent and in-situ operations

Once the Piazzi lander is released from the orbiter, it performs an active descent to correctly target the landing location. The lander is designed to be static and operate from the landing position to collect samples. The active landing is chosen mainly for two reasons. Firstly, the active descent allows hazard detection and avoidance thanks to the Guidance Navigation and Control (GNC) suite on board of the Piazzi lander. Secondly, the control scheme can actively adjust the orientation of the landing platform to ensure the correct operations of sample selection and collection. The descent trajectory is computed with a ZEM/ZEV guidance planning algorithm and lasts about 26 minutes by using a ΔV of 429.3 m s^{-1}. Moreover, the landing gear is designed to be able to damp for about 2.5 m s^{-1} impact speed and has heritage from the Mars and Moon Landing with a TRL of 4.

Once on the surface, the in-situ operations start. The nominal concept of operation aims to collect five different samples from the surface thanks to a sampling mechanism that is placed at the end of a robotic arm (see the following sections for configuration and figures) that is observed from a camera placed on the same arm. The five samples are collected from five different sites around the landing site which are reachable with the robotic arm and safe to sample for the drilling mechanism. The camera is a fundamental instrument for science and operation of the Piazzi lander on the surface as it ensures not only in-situ images to choose the correct sampling sites, but helps engineers to observe the sampling procedure and ensure it is carried out correctly.

The concept of operation for sampling is divided in the following steps:

1. After landing, Piazzi takes a series of 12 images covering the area accessible to the sampling arm.
2. Descent images, housekeeping and landing images acquired by the lander's camera are down-linked through the orbiter to Earth, where the status of the rover is assessed. Drill sites are selected based on the post-landing images.
3. Commands to collect sample 1 are sent to and executed by the lander.

4. Post-drill images and housekeeping data are down-linked to Earth to assess the collection of sample 1 and possibly reevaluate drilling sites selection.
5. If the collection of sample 1 is successful, commands to collect sample 2 are sent to and executed by the rover.
6. Steps 4 and 5 are repeated for each sample.

The nominal time of operation is 10 Earth days, i.e. 26 Ceres days. This implies 52 slots for communication which allows for ground-based decisions before each sampling operation. Several attempts may be necessary before the first successful drill; this would result in the repetition of steps 3 and 4. This timeline has been designed without considering sampling system failures or anomalies. Future studies should define a more robust operational scenario which must consider wider time margins. This implies possible changes in the overall design on lander power system and inbound trajectory as mentioned in the respective sections.

The drilling mechanism is composed of a penetrating drill and a brushing mechanism, as explained in Section 5.2.3, that is used to remove the uppermost space-weathered layer of the surface that may have been contaminated by the engines' exhaust, and a drill with different power increments to collect the samples. Once the sample is collected, the arm places it into a basket in the bus. The process is repeated four times for as many samples, with a fifth repetition placing a sample into the on-board mass spectrometer to determine Ceres' hydrogen, oxygen, and nitrogen stable isotopic ratios and relative abundances of volatile subsurface material. This is done in order to ensure the science margin even in case of failure during sample canister catching, outbound interplanetary trajectory or reentry on Earth. When finished, the arm performs a 360° horizontal rotation to capture a panorama from the landing site.

4.5. Sample canister catching

The lander uses the same algorithm, i.e. the ZEM/ZEV guidance planning algorithm, to design its ascent trajectory. In this case, a trajectory from the ground to the SOO is considered, which lasts 34.17 minutes and consumes 499.54 m s^{-1}. The ascending module is then put on the same orbit as the orbiter, where catching operation can start. This is divided into two different phases: the cooperative rendez-vous and the sample canister catching.

The cooperative rendez-vous starts with a large distances between the orbiter and the ascending module, where the two modules cooperatively and autonomously reduce their relative distance thanks to the autonomous GNC system, outlined in the Section 6.9. It must be noted that the rendez-vous is cooperative as both modules are actively controlled and can modify their attitude and position with the use of thrusters and reaction wheels. When the nominal distance and correct attitude are reached, the ascending module releases the sample canister in the direction of the orbiter's collecting mechanism, which draws inspiration from the Mars Sample return mission [68]. The catching phase starts. The orbiter tracks the sample canister thanks to LIDAR and vision-based navigation until it is captured from the capture cone and it is then placed in the reentry capsule to be stored and safely brought back to Earth.

4.6. End-of-Life disposal and curation facility on Earth

Ceres is classified with respect to planetary protection concerns. As is it a sample return mission, it is classified as a class V mission [20]. The COSPAR comity has established six criteria to decided if a mission should be restricted or unrestricted [20]. Actually, five of the six criteria could be discussed at a global level: there may have been liquid water and metabolically useful energy sources on Ceres in the past, quantity of organics have been detected by Dawn, it is not certain that Ceres has been subjected to extreme temperatures and no proof of a natural influx from Ceres to Earth exists at the present time. Finally, as shown in Castillo-Rogez and Brophy [69], the ionization dose received by each site on the Ceres's surface is the critical point for the sub-classification restricted/unrestricted. Ceres is an old object and in average, the organic matter present on the surface has been exposed to cosmic rays for several million years, which assure the sterilization of the surface :"the sterilization is achieved after about 1 My for superficial material down to 10 cm" according to Castillo-Rogez and Brophy [69]. On the opposite, salts from the Occator faculae have been exposed to cosmic rays more recently and given the uncertainty about the dating of the site, the NASA pre-decadal report [69] concluded that the restricted classification is required for the sample return missions from the Occator faculae. Because of this classification, it is required to understand how the different modules orbiting or located on the surface of the dwarf planet are disposed.

The ascending module is located on an non-impacting orbit around the dwarf planet consistent with the end-of-life orbit of the the Dawn spacecraft, for at least 20 years with a probability of 99%, and for at least 50 years with probability of 95% [70]. The lander instrument suite would remain on the surface.

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This also means that everything that has been in contact with Ceres must be tightly contained or sterilised before and after re-entry. Once the sample has landed on Earth, it would be retrieved and brought to the European Curation of Astromaterials Returned from the Exploration of Space (EURO-CARES) facilities in the UK [71], via refrigerated transport at temperatures below -20°C. At the EURO-CARES facilities, the basket and two of the four sample capsules would be opened in a refrigerated and atmosphere controlled containment chamber. The chamber would be built according to Planetary Protection standards to avoid any contamination of the sample by terrestrial life, contamination of Earth by cerean material, or chemical alteration of the sample. When analysis has mapped any risk and ensured there is no danger of contamination, the opened sample material would be characterized and catalogued, before half of it is distributed to laboratories after a review of their proposed utilization. The other half (i.e. the two remaining capsules) would be preserved for the future generation.

5. Payload

The main scientific goal of this mission is to return to Earth a sample of the Occator Crater faculae for high-precision laboratory analyses. A suite of scientific instruments is necessary to identify the best landing site, to monitor the descent and drilling phase, and to collect geological and physical information about Ceres and its environment. The orbiter would carry a surface-penetrating radar, a thermal infrared mapper, and a narrow angle camera. These three instruments would perform global measurements needed for both landing site selection as well as contextualization of the sample return measurements.

The lander would be equipped with a gas chromatograph mass spectrometer, descent cameras, an arm camera, as well as a drilling and sampling systems. The cameras would provide geological context for sampling site selection as well as support for sampling operations, while the mass spectrometer would yield the first ever in-situ measurements of the composition of an airless body surface.

The presence of scientific instruments on both the orbiter and the lander mitigates the risk of single point of failure since they fulfil the scientific requirements defined in Section 2 to address the scientific objectives of the mission.

5.1. Orbiter

The Calathus orbiter's scientific payload would include three instruments: a narrow angle camera, a thermal infrared mapper, and a radar.

5.1.1. High Resolution Narrow Angle Camera

The orbiter would include a high resolution Narrow Angle Camera (NAC), whose objectives would be to observe and map the surface, providing information about its appearance and morphology. The mapping phases would help finding a suitable landing site.

The Dawn mission mapped a limited area of Ceres with a resolution up to 3.3 m/px achieved on its closest fly-by. The camera on the orbiter would be build on heritage from the OSIRIS Narrow Angle Camera on board of the Rosetta spacecraft [72]. OSIRIS consisted of an off-axis mirror system equipped with backside illuminated CCD detectors, with a field of view (FOV) of 2.2 degrees, comprising 2048 x 2048 pixels with a pixel size of 13.5 µm, and an instantaneous field of view (IFOV) of 18.6 µrad (3.8 arcsec) per pixel [72]. Since the Calathus mission would be more than ten years into the future, the CCD from the NAC on-board Rosetta would be replaced with a more modern one with 4096 x 4096 pixels. It would allow the Occator Crater to be mapped with a spatial resolution of about 0.57 m/px from a distance of 61 km during the low-altitude mapping phase. Surface features of down to 1 m would be resolved and images taken during that phase would be used to select the safest landing site. The resulting images would be improved by a factor six compared to the Dawn's highest-resolution images. Shape reconstruction techniques, such as stereophotoclinometry (SPC) and stereophotogrammetry (SPG), would help achieving subpixel precision by merging different phase angle images [73, 74].

5.1.2. Thermal Infrared Mapper

Thermal mapping of Ceres would provide information on the local and global physical properties of Ceres, such as surface porosity and grain size distribution.

A thermal infrared camera, similar to the Thermal InfraRed imager (TIR) designed for the Hayabusa2 mission [75],

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would yield thermal emissions maps of Ceres. TIM observes in the wavelength range 8 to 12 μm. With a field of view of 16 deg × 12 deg, the TIM (Thermal Infrared Mapper) would be able to characterise the thermal inertia of the landing and sampling site as well as other regions of interests. As the TIM measurements require relatively little power and yield light weight data products (less 200 kb/image), it can be operated along with the NAC during the mapping phase, yielding a global thermal inertia map of Ceres at both daytime and nighttime. TIM is meant to support landing site selection operations by providing information on the global surface roughness while also helping to fulfil several science objectives such as characterising surface properties and mapping Ceres' mineral distribution.

5.1.3. Radar

To investigate the formation of Ceres' faculae, structural information about the cerean subsurface is required. The radar's data would provide the vertical context of the sampling site, which would help in selecting the most appropriate landing site and understand the sample's analyses. Moreover, probing the surface down to several tens of meters, with a resolution a few meters, would shed some light on how these faculae are formed, by emphasising embedded volcanism features, fractures and possibly the salt-rich waters if the radar's waves penetrate at a sufficient depth. The Calathus orbiter would therefore carry a radar inspired by the SHARAD radar designed for the MRO mission (NASA) [76]. This radar would be imaging the first tens of meters of the subsurface minimum, with a vertical resolution of few meters. These two parameters could be evaluated with a better precision by testing the radar's behaviour along with analogues of the subsurface of Ceres, either by direct experiments (as described in [77] for Mars) or by simulations (as described in [78] for Europa). If the bright material observed by Dawn is brought up from the subsurface of Ceres, topographic images of the subsurface area below the sampling site (as well as other faculae featuring craters) might be a key element to support such theories.

5.2. Lander

The Piazzi lander would consist of an hexagonal instrument platform carrying cameras and a mass spectrometer. The lander would also include the drilling system, the sample canister basket, and the ascent module.

5.2.1. Cameras

The lander would include two cameras to provide geological context for the sample and support ground-based decisions about the sampling site. The first would be mounted on the lander body underneath the top deck, and would be built on heritage from the Lander Imaging System (ROLIS) on board the Philae lander. This instrument consists of a miniaturised CCD camera and four independent arrays of light emitting diodes (LEDs) in visible and near-infrared wavelength to illuminate the field of view [79]. This field of view is large of 25° × 25° with 2048 × 2048 pixels: the camera can thus provide a pixel size of 0.15 m at a distance of about 700 m. It would acquire images during the descent of the lander towards Ceres, yielding geological context crucial for scientific investigations but also serving as a monitor of the descent phase. This camera would allow hazardous boulders from about 700 m of altitude to be recognised, which gives margin for safe landing.

The second camera would be mounted on the robotic arm of the lander. The camera is the same as on board the InSight Mars lander and features a resolution of 0.82 mrad/px [80]. The objectives of the camera are monitoring the location of the drilling system, and investigating the geological and physical properties of the landing and drilling site. After landing, 12 images forming a panoramic shot of the area would be used to determine the location of the exact landing site. One *monitoring* image of the first sampling site would be taken after the first drilling and downlinked to ground. If the first drilling is successful, the subsequent drillings would take place and their monitoring images would be downlinked after all drillings commands have been executed. These detailed images can reveal the granular texture of Ceres's surface down to the cm scale, allowing fragments of material of diverse shapes and sizes to be characterised. The size-frequency distribution and shape analysis of these fragments would help to investigate the origin of these elements [81].

5.2.2. Mass Spectrometer

In situ analysis of one collected sample would be performed on the lander by a gas chromatography mass spectrometer similar to the one carried by Philae to the comet 67P/Churyumov-Gerasimenko, Ptolemy [82]. The mass spectrometer would measure the isotopic composition of volatiles present in the collected sample, thus assuring a significant science return in case the other collected samples are not returned to Earth intact. Namely, a measurement of particular interest for the science case is the D/H ratio of the water found in Ceres material, which may provide insight as to whether Ceres-type bodies played a role in the delivery of water to Earth.

5.2.3. Drilling and Sampling Systems

To satisfy the scientific requirements of the mission, four samples of about 4 cm^3 of material have to be collected. One additional sample of 0.5 cm^3 would be analysed by the on-board mass spectrometer to investigate the composition of the surface. Several requirements must be verified during sampling. Firstly, the mechanism temperature during sampling should remain below -20 °C as to preserve the volatile materials. Secondly, the sampling mechanism should drill different types of soils due to the lack of knowledge of Ceres' surface composition: from solid terrain with compressive strength up to 20 MPa to loose material with different adhesion values. Finally, the system should remove the upper layer of the cerean soil up to 5 mm to collect pristine material not affected by space weathering.
The drilling and sampling system would be composed of the four following instruments: a hammering drill to collect samples, a camera to provide feedback, a mechanical grinding device to clean the sampling area and a manipulator to operate the instruments. The hammering drill would take heritage from the CHOMIK instrument carried by Phobos-Grunt [83]. This instrument would be based on the accumulation of electric energy which is then released from an electromagnetic system in form of strokes to create the torsional and linear movement of the drill [84]. A detachable sampling container, made of hardened titanium with diamond inserted at the bottom, also plays the role of a drilling bit [85]. The length of the cylindrical sampling container would be of 5 cm in order to ensure the required 4 cm^3 of material per sample. The 2-meter long manipulator would be based on already available systems with profound space heritage, like InSight [86], or technologies maturated for flight, such as the Phobos-Grunt [87] manipulator (in Figure 5). Moreover, the mechanical grinding device would be made with bristles made of titanium and a motor would be in charge of the grinding movement.

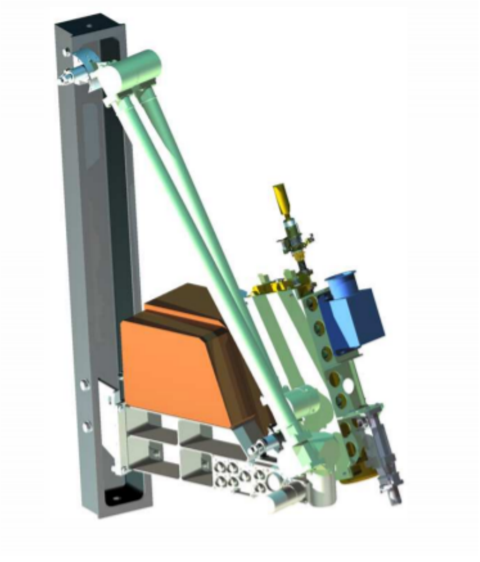

Figure 5: The Phobos-Grunt manipulator (see [85])

6. Spacecraft bus and lander design

The Calathus spacecraft, in Figure 6, would consist of a box with dimensions 4.75 m × 4.27 m × 4.27 m. It would include a rendez-vous system, a high-gain antenna, two 9.5 m size solar panels on the orbiter. The lander is battery powered and attached to the orbiter until release. The final launch configuration would fit the allowed fairing volume as shown in Figure 7.

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6.1. Mechanical Subsystem and Mechanisms

The orbiter structure has been designed to allocate all the instruments and the propellant tanks. A central cylinder, located in the bottom part of the orbiter, ensures the correct attachment on the launcher interface ring which increases the stiffness to launch loads. The propellant tanks are designed to allocate the needed propellants, i.e. the xenon and the chemical. The two central tanks, in Figure 8, are designed in titanium to allocate the xenon required for the ion thrusters; whereas the four circular tanks are used for the chemical bipropellant propergol storage. The pressurising system is not shown in Figure 8. The orbiter structure is composed of Carbon-Fiber-Reinforced Polymer (CFRP) sandwich panel to ensure rigidity and low weight. Stresses caused by launch are distributed on the structure thanks to the central cylinder where the xenon tanks are, as presented in Figure 8. The structure material is widely used in space missions, with high TRL and heritage from LISA and Dawn spacecraft.

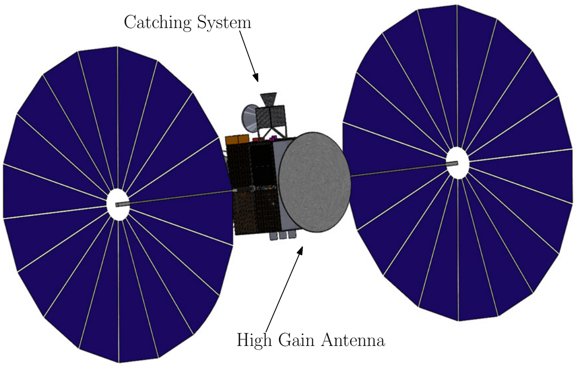

Figure 6: The orbiter after the deployment of the solar panels

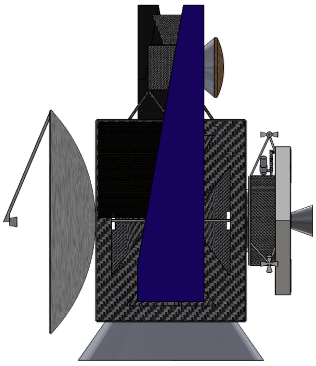

Figure 7: The orbiter closed as in the Ariane 64's fairing

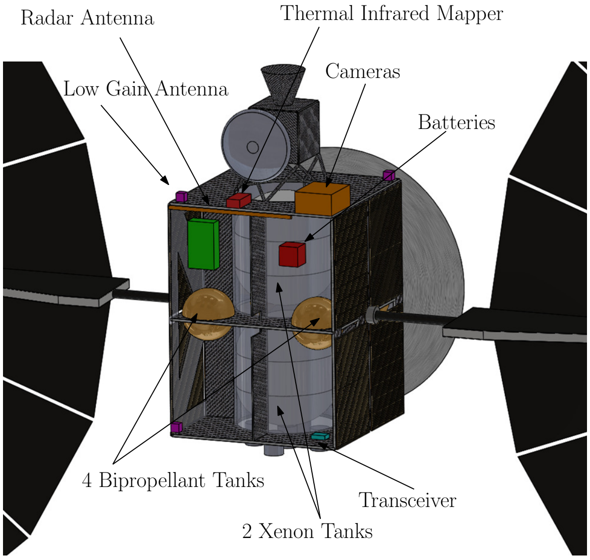

Figure 8: The allocation of the orbiter components in the orbiter

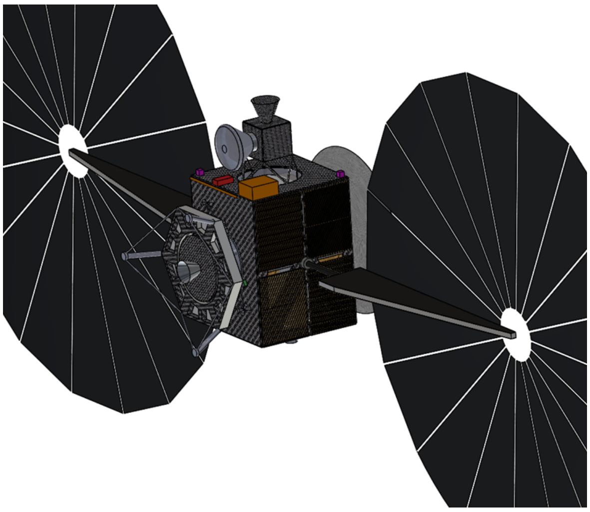

Figure 9: The lander attached to the orbiter structure

As shown in Figures 8 and 9 the catching system is on the top part of the orbiter, where instrumentation and cameras are placed, and the lander is placed on the side. Figures 10 and 11 show the top and bottom view of the lander, designed with CFRP sandwich panels while a beam structure is used to ensure a light module that minimises the fuel consumption during ascent whilst ensuring the load is distributed during landing. The instrument platform is designed to have holes where instruments, such as the mass spectrometer and the camera, are located to assure the thermal requirement and to reduce the mass of the overall structure. In Figure 12, the three main subsystems of the Piazzi lander are shown. In particular, it is important to note the ascending module configuration where the attitude thrusters, the central manoeuvring nozzle and the hydrazine tanks are shown.

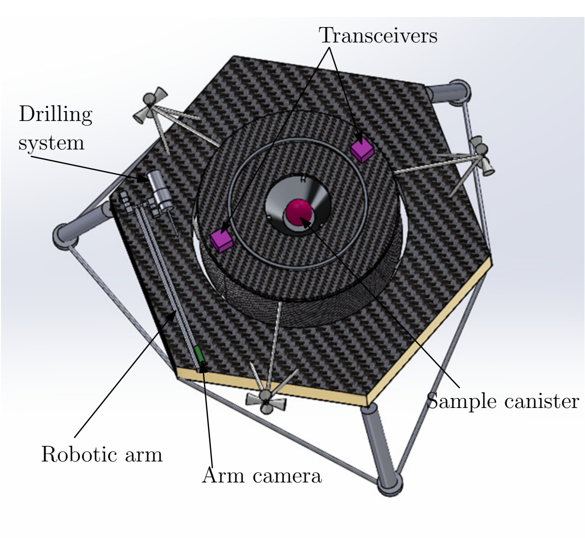

Figure 10: The top view of the lander

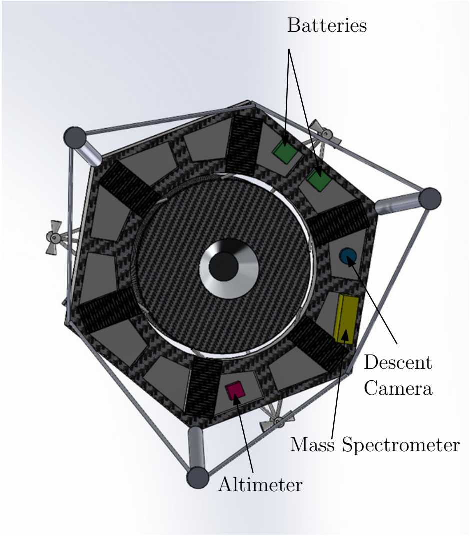

Figure 11: The bottom view of the lander

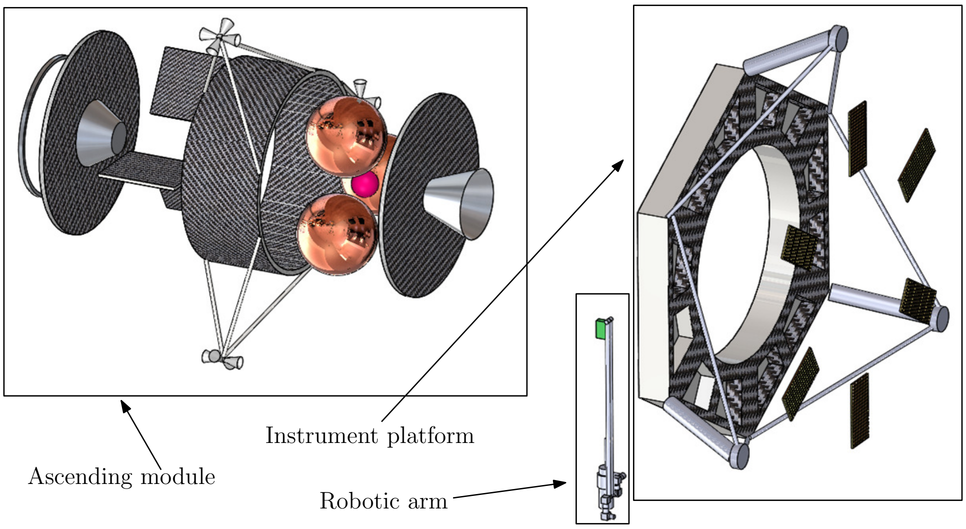

Figure 12: The allocation of the lander components in the lander

6.2. *Propulsion Subsystems*

Three independent propulsion systems are required for the mission: high specific impulse ion thrusters for the Earth-Ceres-Earth transfers, a bipropellant NTO/MMH (nitrogen tetroxide/ Monomethylhydrazine) thruster for impulsive manoeuvres close to Ceres, and a hydrazine monopropellant thruster for the lander. Using current technology, about 2 tons of xenon would be needed if QinetiQ T6 ion thrusters were used [88], and about 900 kg of NTO/MMH would be required using an ArianeGroup S400-15 thruster. As the required propellant for both the ion thruster and the bipropellant thruster is so high, it would be interesting to qualify QinetiQ T6 at an operation point of higher I_{sp}. A dedicated high I_{sp} ion thruster could also be considered for the mission, as was done for the BepiColombo spacecraft

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where it led to a reduction in xenon mass to 580 kg. This improvement would be justified by the fact that reducing the xenon mass directly influences the cost of the mission. In fact, the annual world-wide production of xenon is about 53 tons and the use of 2 tons for the mission implies high cost.

The lander propulsion system uses hydrazine as propellant which is stored in 3 tanks placed in the ascending module (see Figure 12). A central thruster is used for the ascending and descending trajectory control.

Both the orbiter and the lander use helium for pressurisation of the tanks (2.7 and 0.4 kg respectively) and a cluster of 12 thrusters for attitude control which use hydrazine or the bipropellant NTO/MMH for the lander and orbiter respectively.

6.3. Communication Subsystem

The communication subsystem is driven by two main parameters: distance and data amount. The maximum distance between Ceres and Earth in a theoretical Ceres-Sun-Earth constellation is 3.976 AU. The amount of mapping data (without source coding) is 166.66 Gbit. Surface mapping is key for choosing a suitable landing zone and therefore the data shall be downlinked as fast as possible, using a Ka-Band System which can provide sufficient downlink speeds of up to 360 kbit/s at maximum separation. A 3 m High Gain Antenna (HGA) is used on the S/C to ensure the link and provide the needed performance.

The payload data system would rely on the Deep Space Network (DSN) for Ka-Band. In addition the telemetry and telecommand subsystem would use a low power, low gain X-Band emergency system which would ensure communication at any attitude and would be built to ensure communication in emergency situations where power management is crucial. The expected data rate would not exceed 50 bit/s which is sufficient for emergencies in any mission phases.

Communication between orbiter and lander during surface operations must also be considered. This system would work in X-Band with the available X-Band antennas of the orbiter. The orbiter and lander would have a maximum distance of 500 km. Even with a lower power system of 15 W sending power and low gain antennas, 80 kbit/s can be reached with a Quadrature Phase Shift Keying (QPSK) modulation. The gathered data from the lander would then be stored and relayed to Earth with the Ka-Band payload data system. The orbiter uses the already available X-Band radio system for this type of communication, while the lander carries a Ka-Band radio system, which provides the aforementioned data rate and sends power paired with an antenna that provides a circular gain pattern

6.4. Data handling Subsystem

The design of the On-board Data Handling (OBDH) subsystem is mainly driven by the long mission duration, the limited down-link capacity to the ground station and the power requirements on the lander. The long mission duration makes hardware with ample flight heritage favourable. Due to the limited down-link capacity to the ground station, mass memory on-board is required. European heritage, such as the LEON-FT processor, are preferred. Out of these factors, the design is mainly driven by memory requirements, leaving the processing power as secondary importance. The Next Generation On Board Computer by RUAG, which has mass memory modules available in different sizes, is suggested for the orbiter.

Data rates of different mission phases are taken into account to decide on the orbiter memory. The most data intensive phases are the mapping phases, where a large amount of images has to be stored before they can be down-linked. After the mapping phase, a maximum of 167 Gbits need to be stored and down-linked in the following 133 days. Therefore a NAND Flash Module - DDC with 196 Gbit is chosen. The case of storing the full series of images during the mapping is considered as a worst case scenario.

The Processor Board from RUAG, due to its smaller form factor, is suggested as the computing module for the lander, while a mass memory has to be added separately. The Processor Board can be optionally equipped with the RTAX 2000 FPGA, which might be of interest for the computationally expensive control algorithms for the landing procedure.

6.5. Power Subsystem

Since no feasible alternative to a solar power generator for the mission timescale and power ratings is conceivable, the spacecraft is powered by state-of-the-art multi-junction solar cells designed for low-intensity applications. Sample preservation issues demand short time-of-flight for the Ceres-Earth orbit, therefore the preliminary design of the size of the solar power generator is driven by the power required by the ion engines to fulfil the thrust profile for the designed orbit. In this case, a class 100 kW Begin-of-Life (AM0) solar array is required. Although such a power rating represents a technological challenge, new promising solutions could be tailored for the needs of the mission due to their flexibility, modularity and scalability. As a first-approach design, the MegaFlex Solar Array technology [89] is considered, leading to a structure consisting of two circular flexible panels with a diameter of 16 m. Further iterations of the orbit design would lead to an optimized solution and would reduce the solar panels area significantly. The energy storage system for the spacecraft is expected not to pose any technological challenges. The orbiter is equipped with a battery system based on Li-Ion 18650 cell technology with a nominal capacity of 7.5 kWh, capable of powering the spacecraft during eclipse and recovery phases. The lander, on the other hand, is equipped with a redundant dual battery system (primary + secondary). The primary battery is based on $LiSOCl_2$ technology, equipped with a de-passivation circuit to remove the passivation layer formed during the cruise phase. Ground testing on a twin battery would facilitate the estimation of the capacity during the landing and scientific operation phases. The secondary battery is based on re-chargeable Li-Ion technology. It is supplied by the orbiter solar panels via umbilical line during the cruise phase. Within the 10 Earth days required to perform the scientific operations at Ceres' surface, an optimized schedule of the drilling phase with the data transmission windows leads to a minimum battery capacity of 3.8 kWh [90]. The scientific operations at Ceres, scheduled within 10 Earth days, may be subjected to significant delays due to anomaly procedures. Further iterations on the science operation schedule at Ceres surface have to be performed to account for this scenario, which can lead to an increased size of the secondary battery and to a customized solution for a lander solar generator.

The ascent module is equipped with a primary battery of the same technology. In this case, to ensure the worst case autonomy of 48 hours during the ascent and docking phase, a total capacity of 1.4 kWh is required. All the batteries are equipped with thermistors and heaters to ensure proper temperature control in the optimal storage range provided by the manufacturer. The sizing has been done taking into account a subsystem margin of 20%.

6.6. *Thermal Control Subsystem*

The thermal control subsystems of the orbiter and the lander ensures the correct temperature of all subsystems during the whole mission. From the mission requirements, no separate thermal control measures have to be implemented on the samples at any point. Table 2 depicts the temperature requirements for the spacecrafts and the respective subsystems, which limit the allowed temperature ranges.

Table 2: Temperature range requirements

	T_{min} [°C]	Limiting subsystem	T_{max} [°C]	Limiting subsystem
Orbiter	25	Xenon propellant	40	Camera and electronics
Lander	10	Hydrazine propellant	40	Camera and electronics

As the dominant mechanism of heat exchange between the spacecraft and its environment is thermal radiation, a combination of radiators including louvers, which are controlled passively by bimetal springs, multi-layer insulation, heat pipes and small polyimide heaters would be sufficient to regulate the temperature of the two spacecrafts with minimal power consumption. The proposed system can cope with the unsteady thermal environment of the spacecraft, especially during the two most extreme cases of the mission: the hot first phase of the mission, during which the spacecraft experiences the greatest heat flux from the Sun, and the cold environment both orbiter and lander have to withstand in later mission phases at Ceres. Tables 3 and 4 depict the contrast of these two most extreme thermal cases for the orbiter and the lander.

Table 3: Thermal environment of the orbiter

Case definition	Sun heat flux [W/m²]		Infrared emission [W/m²]		Albedo [%]	Equilibrium temperature [°C]	
	Min	Max	Min	Max		Min	Max
Earth Escape	0	1414	216	258	34	-81.1	78.2
Ceres 100 km orbit	0	159.5	14.6	81.7	9	-138.9	-71.5

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Table 4: Thermal environment of the lander

Case definition	Sun heat flux [W/m²]	Infrared emission [W/m²]	Conduction [W/m²]	Surface temperature [°C]
Daytime at Ceres	159.5	144	0.4	-40
Nighttime at Ceres	0	26	1	-143

6.7. Navigation and Control system

Two separate navigation and control subsystems are required for the Calathus mission, one on the orbiter and on the Piazzi lander. The navigation system of the orbiter is composed of star trackers (5 arcsec precision), sun sensors, Inertial Measurements Unit (IMU) and navigation cameras with a field of view of $25° \times 19°$ and 2592×1994 px. The Piazzi lander carries a set of sensors to allow landing and orbital operation during ascent and on-orbit operation: star trackers - to be used in the orbital phase - IMU, navigation camera and an altimeter, to allow landing.

The control system of the orbiter is composed of reaction wheels and ACDS thrusters to allow pointing and compensate perturbations. The same sensors are carried by the lander in order to ensure the correct orientation of the instrument suite during descent, landing and ascent.

The main driving factor for determining the control system for the orbiter is the orientation velocity required to have pointing during low altitude mapping of the cerean surface, as the camera must be pointed towards the crater: this implies an angular velocity of about 0.1 deg/s provided by the reaction wheels and a pointing precision of 50 arcsec. A momentum dumping of about 2 N given by the thrusters is required after wheel saturation and it is crucial to design the thrusters cluster for this and for housekeeping manoeuvres.

The main driving requirements for designing the lander control subsystem is to ensure the correct orientation of the lander during the descent trajectory so the instrument platform is correctly oriented. The reaction wheels are crucial to provide the required angular velocity of 0.04 deg/s. This requirement has been deduced from the guidance trajectory introduced in Section 4.4. Moreover, in order to brake the spacecraft during landing, the thrusters are designed to provide force of 0.25 N which is consistent with the proposed trajectory. The navigation suite has been designed to provide a precision of about 75 arcsec by combining laser altimeter, navigation camera and IMU.

Both the lander and the orbiter are equipped with a cluster of 12 thrusters which allows redundant control in all translational and rotational directions. Reaction wheels are redundant to avoid system failure (for example as occurred during the Hayabusa mission [91]). Similarly to previous mission to small bodies [91, 92, 93, 94, 95], the critical navigation sensors, such as navigation cameras, star trackers and IMUs, are redundant to minimise mission failure. A set of 16 Sun-sensors are used as in previous missions. The altimeter of the lander is similar to the laser-range finder used by the Hayabusa2 probe as it is less power demanding that the flash LIDAR carried on OSIRIS-REx [96].

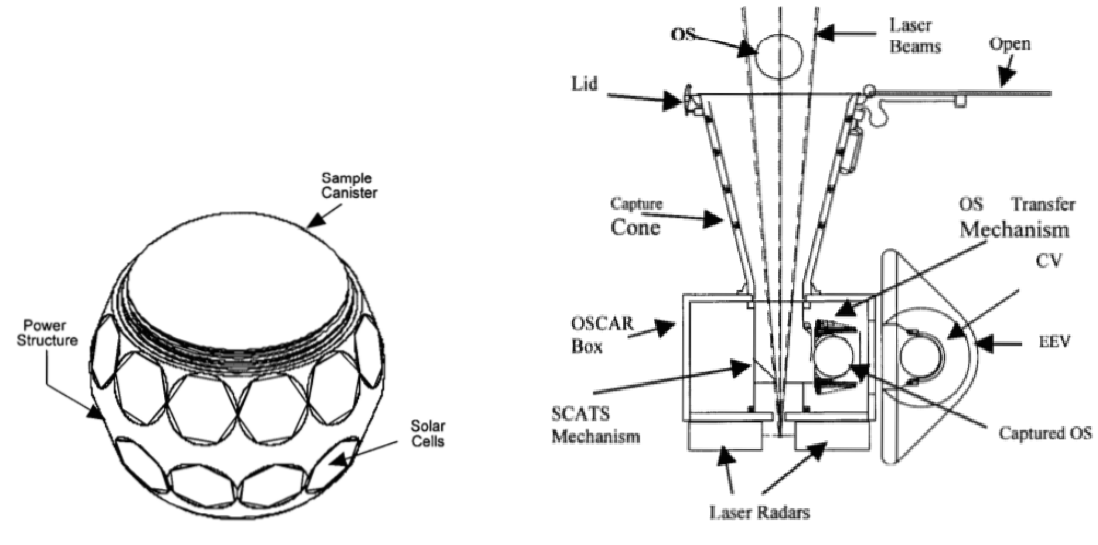
6.8. Landing System

The mission is expected to use active landing with obstacle avoidance software. This subsystem is required to ensure low velocity impact and safe landing. A critical subsystem is the landing gear to damp the residual velocity and ensure structural integrity. This is a crucial issue that can take advantages from the heritage of previous lunar, martian and small body missions. Nevertheless, it is important to notice that Ceres has its own peculiar environment to be considered: neither a extreme low-gravity body, which implies problem in bouncing and anchoring to the surface, nor a dwarf planet with atmosphere, which implies aerodynamical forces during descent. The absence of these two problems implies that landing on Ceres is expected to be easier to accomplish. Further analysis should be conducted to identify the subsystem requirements and the subsystem optimal design. Moreover, as the mapping of the landing site would have a resolution of 0.6 m/px, an active hazardous detection and avoidance system is necessary to fulfil mission requirements (see Section 3). This system ensures that the lander can dodge boulders and other obstacles in order to land at a hazardous-free spot close to the nominal landing site. This technology has not been used on other celestial bodies. A first try of hazardous detection and avoidance will be implemented in the Chinese mars lander set to launch in 2020 [97] and, as a consequence, further technological development is required. The nominal algorithm would be based on cameras and LIDAR data fusion for safe and pinpoint landing [98].

6.9. Sample Canister Catching Subsystem

A crucial operation for the Calathus mission is the sample canister catching. This implies that a careful design must be put in place in order to ensure the fulfilment of mission goals. The main heritage of this design is Mars

Sample Return [68] for the canister catching and identification during flight. The cooperative rendez-vous design is based on the experience obtained from the ATV and the design of vision-based navigation solution for cooperative rendez-vous in the Earth environment [99, 100, 101].
The first phase is the cooperative rendezvous between the two spacecrafts. The control systems of the orbiter and the ascending module are used to keep the relative position and orientation correct while the relative navigation is ensured by a continuous radio communication, which is obtained from the LGA carried from both spacecraft. The use of the LGA ensures that even when the two spacecraft are distant, relative localization and position can be performed by knowing the position and velocity in the cerean reference frame. Thanks to this information the two spacecraft can operate and reduce their spacial separation. Then the close approach between the two spacecrafts starts. Vision-based algorithms, such as spacecraft model tracking [99, 100], ensures that the orbiter correctly localises and orients itself with respect to the ascending module. This phase starts when the two spacecrafts have a spatial separation of about 150 m that allows the main spacecraft to identify shape details in the image of the ascending module to be matched with the model during tracking. When the first phase is completed, the canister is ejected from the ascending module. This phase starts when the spatial separation between the two spacecraft is 25 m. In order to correctly localise the canister, it is covered in LED lights and solar cells (which ensure high reflectively with respect to incident laser beams), which can be tracked from the navigation camera. Laser pulses are emitted from the LIDAR on the orbiter, which ensures accurate localisation of the canister at close distance. The tracking is supported by the same vision-based navigation with model tracking as the previous phase. The LED tracking technique is similar to the technology that has been used for the touchdown operation of the Hayabusa2 spacecraft at Ryugu [102]. The relative orientation and position is controlled accordingly to ensure that the sample canister enters in the capture cone, as depicted in Figure 13b. Once the canister is inside of the main spacecraft, a sliding mechanism pulls the sample canister into the reentry capsule.



(a) The sample canister

(b) The catching system

Figure 13: The Mars Sample Return heritage (see [68])

6.10. Re-entry capsule

Since a sample return mission to Ceres falls under class V restricted regulations, the re-entry capsule has to follow a very tight design guideline. The sample is under no circumstances allowed to contaminate Earth when returning to Earth. Therefore a crushable structure is suggested [103] which would take the whole load of the impact. A parachute is not considered since it could for instance rupture and then a harder than expected impact could result in contamination. A landing in water is not allowed although the transport container would be water tight. Only three possible landing zones exist on Earth: the great salt desert in Utah (USA), the Kazakh desert in Kazakhstan, and the Australian Woomera desert. The landing site would be selected when the return trajectory is well known. The nominal re-entry would be in the Woomera desert as the Australian government has experience with the recovery of reentry capsule as performed during the Hayabusa mission. The design of the reentry capsule is taken as heritage from previous missions concept, such as Mars Sample Return's capsule [104].

7. Mission budget and risks

7.1. Mass budget

The preliminary wet mass budget estimate for Calathus is of 5880 kg (including 20% system margin and the launch adapter) as presented in Table 5. Considering the Ariane 64 launch capacity of 7667 kg, a launch margin of about 1520 kg is available, which makes is possible to embark a small spacecraft, possibly a secondary science payload, together with Calathus. The fuel comprises the most critical part of the mass budget which is 3373 kg, which is essential to achieve the itinerary to Ceres.

Table 5: Launcher and spacecraft current best mass budgets estimates.

Mass Budget	Mass [kg]
GNC	46
Communications	103
Data Handling	20
Instruments	53
Mechanisms	97
Propulsion	373
Power	758
Structure	379
Thermal Control	83
Harness	94
Spacecraft Dry Mass (including 20% system margin)	2407
Mass consumables	3373
Wet mass	5780
Launcher adapter	100
Total wet mass + Launcher adapter	5880
Ariane 64 launch capacity	7400
Margin	1520

7.2. Power budget

For the Calathus mission, the main power consumption modes are highlighted in Tables 6 and 7. The power consumption of each mission phase is reported for each subsystem, considering worst case operations and a 20% subsystem margin. The power required by the ion engines during the inbound and outbound trajectories is by far the main driver for the solar panel design. For this reason, the propulsion power has been intentionally omitted in this section.

7.3. Programmatics

Within ESA's Cosmic Vision framework, the Calathus mission would be classified as an L-class mission. It is expected to produce answers to some fundamental questions about the evolution of asteroids in the Solar System, astrobiology, and the delivery of volatiles and organics to Earth. Although estimating cost is challenging, it will be a programmatic challenge to ensure the budget for the mission does not exceed the cost cap of 1000 ~ M€ for L-class missions. This is in part due to the multiple elements of this mission, and the large number of technologies involve. Additionally, planetary protection technologies are a large driver of cost, as engineering decisions have been made which, whilst favourable to reduce planetary protection concerns, may be more expensive. An example of this would

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Table 6: Power modes for the Orbiter and Orbiter subsystems: Attitude and Orbit Control (AOCS), Communication (COMS), Data Handling (DH), Payload Instrumentation (PAY), Mechanism (MEC), Power distribution (POW) and Thermal Control (THER).

Orbiter Mode	AOCS [W]	COMS [W]	DH [W]	PAY [W]	MEC [W]	POW [W]	THER [W]	TOTAL [W]
Mapping	36	0	23	45	12	18	22	157
Comm	36	503	23	0	72	18	22	675
Relay	36	523	23	0	72	18	22	695
Sample Catch	36	0	23	0	42	18	22	142
Eclipse	36	0	23	18	12	18	22	130
Safe	36	80	23	0	12	18	22	192

Table 7: Power modes for the Lander and Lander subsystems: Attitude and Orbit Control (AOCS), Communication (COMS), Data Handling (DH), Payload Instrumentation (PAY), Mechanism (MEC), Power distribution (POW), Thermal Control (THER) and Propulsion (PROP).

Lander Mode	AOCS [W]	COMS [W]	DH [W]	INS [W]	MEC [W]	POW [W]	TC [W]	PROP [w]	TOTAL [W]
Descent	37	0	6	8	0	3	5	58	118
SciOps	0	0	7	2	70	3	5	0	87
Idle	0	0	1	0	0	3	5	0	9
Ascent	37	0	7	0	0	3	5	58	110
In Situ	0	0	7	10	0	3	5	0	25
Transmission	0	55	7	0	0	3	0	0	65

be the re-entry capsule for which special attention will have to be applied in order not to contaminate the Earth after landing.

Comparisons can be made to similar missions, for example OSIRIS-REx cost \$1.16 billion, with \$588.5 million for spacecraft development, \$183.5 million for the launch vehicle and \$283 million for 9 years of operations [105]. However, Calathus does have more elements including separate orbiter and lander segments. In fact, current estimations calculate the most expensive aspect is the orbiter segment. This is because the cost estimate is calculated by multiplying correction factors (depending on complexity) by the dry mass. The costs lowers when payload or techniques are already tested and used. A deeper analysis of the mission's subsystem could help refining the cost estimation.

When considering the risks presented by this mission design, the low TRL of enabling technology must be considered. The success of the mission depends on the presence of some technologies with current TRL levels of only 3 (e.g. the sampling mechanism) and 4 (e.g. active descent) in order to achieve the scientific objectives. However, with a launch date in 2031, at the time of writing there is still 11 years of development time for these low TRL technologies, and as such the risk here is acceptable. For example, the sample capsule ascent and docking with the main spacecraft mechanism is being developed as part of Mars Sample Return, so it is anticipate that despite its low TRL, this would be adequately developed by the launch window [68].

Another concern is the issue of Planetary Protection. Due to the class V restricted nature of samples returned from Ceres, an additional risk is the terrestrial contamination both of the samples collected and back contamination of Earth with the returned samples. To tackle the former, the lander ascent/descent manoeuvres would be controlled using a monopropellant hydrazine thruster to reduce the amount of contamination of the surface of Ceres, and the collected samples would be stored in the sealed reentry capsule until it reaches the curation facility on Earth. For protection of Earth, the re-entry capsule would not use a parachute, and would have a crushable structure to minimise chance of the capsule breaking upon impact.

8. Conclusion

In this paper, the case for a return to Ceres and for a sample of this dwarf planet to be returned to Earth is outlined. The Calathus mission is a concept that aims to bring 4 samples of 4 cm^3 of the bright carbonate material from Ceres' Occator Crater by 2050. This is to understand the astrobiological potential of relict ocean-bearing worlds, and also the origins and dynamics of the Solar System's configuration — and in doing so, to understand how water was delivered to Earth, along with the organic molecules that could through time evolve into life.

A sample return mission to Ceres is the ideal next step in ESA's plan to understand the Solar System, and in doing

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Table 8: Estimation of the mission's cost

	Cost (Million €)
Orbiter	2.7
Lander	0.72
Development and Manufacturing	3335
Ground segment	148
Launcher	132
Grand total	~ 3600

so to ultimately understand life's origins. The technology developed and trialled during Calathus would enhance the likelihood of the actualisation of future missions high in ESA's priority for outer Solar System exploration, including sample return from the more-technologically demanding Jovian and Saturnian moons. In essence, however, Calathus represents the exploration of a fascinating world within its own right. Ceres is a world rich in water, organics, and has a geologic history open and prime for in-situ exploration. Calathus could become humans' eyes and hands on the ground before returning to Earth — the first mission to ever do so on a planet-sized body. The Calathus mission is therefore Europe's means of leading humanity's next flagship, historic space mission, one in the vein of Rosetta-Philae and Cassini's Huygens probe: a means of pioneering the next step in the evolution of spaceflight.

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10. Authors contribution

The author list is divided in three different lists. Oriane Gassot and Paolo Panicucci managed the coordination among the other authors to make this paper possible. The name appearing in the first alphabetical list, from Giacomo Acciarini to Clemens Riegler, have worked on the paper redaction and mission design after the Post Alpbach Summmer School Event 2018. The other authors have contributed to the design during the Alpbach Summer School and the Post Alpbach Summmer School Event 2018.

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