D-Type **E**xplorer for **S**ubsurface **I**nterior sample **RE**turn

Team Orange

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Abstract

The origin of our Solar System has for decades been a mystery and thus the main topic of many recent research studies and space missions. Despite the improvement of instruments, questions still remain about the Solar System's components, origin and evolution. Our current knowledge is based on astrophysical predictions, the study of meteorites and theoretical models. To get further insights on the chemical and physical properties at the time of Solar System formation, knowledge of unaltered (primitive) material is required. Those materials might be represented by the Tagish Lake carbonaceous chondrite, which may be linked to a Near Earth D-type asteroid. For this reason, returning sample material to Earth from such a body becomes mandatory.

In this context, we suggest the DESIRE (D-type Explorer Subsurface Interior sample REturn) Mission to return sample material from the Near Earth D-type asteroid 2002 AT4. The first part of the paper will focus on the scientific objectives and related requirements. The second part will describe the mission operations and highlight the subsystems required to meet the scientific objectives.

Key words: *Space mission, sample return, Near-Earth D-type asteroid, Solar System*

I. SCIENTIFIC BACKGROUND

According to current Solar System formation theories, the Sun and planets formed 4.568 billion years ago from a contracting presolar cloud, evolving into a flattened disk known as the protoplanetary disk around the protosun. Eventually, planets and other Solar System bodies formed through accretion of dust grains in the disk, with remnants of this process being found in carbonaceous chondrites. For example, chondrites contain Calcium-Aluminium-rich Inclusions (CAIs), which were the first condensates to form in the protoplanetary disk. CAIs are highly refractory, and have been used to measure the age of the Solar System. Chondrites also contain chondrules, molten, spherical silicate droplets, whose formation is not yet well understood. Small bodies formed far from the Sun and were not subjected to the same heating processes which led inner Solar System bodies to differentiate, eventually forming the major planets and moons through collisions. These small bodies are believed to have preserved the composition of the primitive material of the protoplanetary disk, thus opening a gateway back in time to before planetary formation. The study of the interior of these small bodies, such as asteroids and comets, can therefore increase our knowledge of the formation and evolution of the inner Solar System.

Even though small bodies contain remnants of the past, they have been shaped by thermal and dynamic processes throughout the evolution of the Solar System. Through previous space missions and Earth-based observations, our knowledge of the physical properties and distribution of these bodies has increased. Today, models exist of planetary migration and other processes forming the current state of the Solar System, and the migrations of the giant planets are believed to have played a large role in shaping the Solar System according to the Nice and Grand Tack models (e.g. [25]). The Main Belt is thus thought to consist of bodies formed in all regions of the Solar System. There are, however, still gaps in our knowledge of the formation and evolution of the Solar System, and missions to the small bodies are therefore desired. For example, unanswered questions regarding the initial spatial distribution of the small bodies and the initial condition of the protoplanetary disk and planetesimal formation remain. Furthermore, increased knowledge of the composition and internal structure of the primitive material can be obtained from the study of these bodies.

Small bodies can also shed light on a time predating the formation of the Solar System. Meteorites have been found to contain presolar grains - solid matter dating back to the stellar nucleosynthesis in presolar stars. The isotopic composition of the presolar grains therefore differs from the primitive composition of the Solar System, and can give insight into the astrophysical nuclear processes in their parent stars[1].

Previous space missions have investigated a small portion of the various asteroid classes, with some returning surface material to Earth. This material has, however, been subjected to altering processes such as collisions and space weather. Therefore, to obtain the most primitive, subsurface material, a further sample return is necessary.

D-type asteroids are believed to constitute the most primitive class of asteroids in the Solar System. D-type asteroids typically feature low albedo (0.03-0.08) and a reddish spectra with no significant features [13]. Based on current knowledge, the surface material of these asteroids is believed to contain organic-rich compounds, carbon, hydrous and anhydrous silicates, with the interior containing water ice. The majority of D-type asteroids are found at the outer edge of the Main Belt and beyond, but a few asteroids that can be classified as D-types based on their albedo and spectral properties are found on Earth-crossing orbits [3].

Due to their low albedos, the possibilities of Earth-based observational studies on D-types asteroids are limited. The number of meteorites linked to this spectral class is also very low. In the currently collection of classified meteorites, only 0.03% belong to ungrouped carbonaceous chondrite-like material, with this characteristic being required to link the meteorite to a D-type parent body. Only one meteorite is considered a highly probable D-type fragment: the Tagish Lake meteorite. Based on the physical properties and composition of this meteorite, the suspicions of especially primitive properties of the D-type asteroids has increased.

DESIRE will, as the first subsurface sample return mission to a D-type asteroid, provide insight into an essentially unexplored class of Solar System objects. A sample returned to Earth, where dedicated instruments providing increased accuracy are available, is the only way to investigate the nature of the primitive material expected to be found beneath the dark surface of the target asteroid. This will enable investigations of the age, structure and composition of, for example, CAIs, chondrules and presolar grains, thus providing knowledge the presolar formation and the chronology of events leading up to the formation of the Solar System planets. This is not possible using solely the Tagish Lake meteorite, as it is the only potential D-type analogue material on Earth. This is why a direct confirmation of the link between Tagish lake and D-type asteroids is desired. [15]

The mission will characterize the physical properties of the D-type asteroid, as well as investigate the depth of the regolith layer and the internal structure of the asteroid, an area essentially untouched by science due to the lack of direct measurements. From the study of both processed surface material and more primitive remnants of the asteroid interior, many additional scientific questions can be addressed, such as the accretion and collision dynamics and effects of space weather on small bodies.

II. Scientific Objectives and requirements

In this section we give an overview of the questions we are going to answer with DESIRE, forming our scientific objectives and going on to form our scientific requirements. We also present the target selection process and requirements for the asteroid sample and instruments to achieve our scientific goals.

i. Scientific Objective 1: SO1

What were the building blocks of the solar system and how did it evolve?
Scientific Requirement 1 SR1: Determine the chemical composition and morphology of the building blocks at the time of the early Solar System formation. We need to measure the elemental composition by spectroscopy and the particle sise and shape by sample analysis.
Scientific Requirement 2 SR2: Characterise collisional history of primitive bodies. We need mineralogy to look for shock metamorphism in the sample material. Determination of the internal structure of the asteroid is required.
Scientific Requirement 3 SR3: Determine the initial spatial distribution and migration of small bodies across the Solar System. Chemical abundances as well as isotopic ratios are required.

ii. Scientific Objective 2: SO2

What are the physical properties of Near Earth Asteroids (NEAs)?
Scientific Requirement 4 SR4: To characterise D-type asteroids. For this purpose, we need to measure: global surface topography by mapping and imaging; composition and mineralogy; sample analysis; and internal structure.

iii. Scientific Objective 3: SO3

How were the building blocks of life formed and transported inside the Solar System?
Scientific Requirement 5 SR5: Characterise organic compounds present in primitive bodies. To do this, we require to identify organic compounds.

iv. Scientific Objective 4: SO4

What was the astrophysical context at the time of Solar System formation?
Scientific Requirement 6 SR6: Determine the presolar grain sources. To do this, we require isotopic ratios of the asteroid subsurface sample.
Scientific Requirement 7 SR7: Characterise stellar processes. Isotopic and chemical characteristics of presolar grains in the sample are required to be measured.
Scientific Requirement 8 SR8: Characterise stellar processes. Isotopic and chemical characteristics of presolar grains in the sample are required to be measured.

v. Scientific Objective 5: SO5

Can the Tagish Lake meteorite be linked to a specific spectral class of asteroids?

	2002 AT4			
	Min.	Nominal	Max.	Reference
Type		D		[30]
Diameter [m]	270	320	380	[30]
Rotational period [h]	6	6	6	[30]
Albedo	0.05	0.07	0.1	[30]
Bulk density [g/m^3]	1.3	2.0	2.7	[30]
Magnitude [mag]	20.8	21.3	21.8	[30]
Thermal Inertia [J/$m^3Ks^{1/2}$]	40	200	2200	[30]
Semi-major axis [AU]		1.867		[21]
Orbital period [yr]		2.55		[21]
Eccentricity		0.446		[21]
Inclination [deg]		1.50		[21]
Δ V [km/s]		5.55		[21]

Table 1: *Properties of target Asteroid 2002AT4.*

Scientific Requirement 9 SR9: Testing whether D-type asteroids are the parent body type of the Tagish Lake meteorite. Therefore we require the chemical composition and isotopic ratios.

vi. Scientific Objective 6: SO6

What are the processes that affect the physical properties of asteroids today?
Scientific Requirement 10 SR10: Characterise the interaction between the solar wind and asteroid surfaces. Therefore we require imaging of low energy neutral atoms.
Scientific Requirement 11 SR11: Determine the collisional record of D-type asteroids. This is done by imaging of the asteroid's surface as well as looking at the mineralogy of the sample.

vii. Scientific Objective 7: SO7

To obtain more information for future defense strategy.
Scientific Requirement 12 SR12: Characterise NEAs in order to plan future defense strategies. To do this, we require information about the chemical and physical properties of the asteroids.

III. Scientific Requirements

i. Target Selection

Based on the requirement to obtain primitive material, we selected near Earth D-type asteroids as our mission target. Currently there are nine known asteroids with this taxonomic classification in Near Earth Orbits [12]. From these, asteroid 2002 AT4 was selected due to its low rotation rate and diameter that is suitable for the mission. The low orbital inclination as well as the low Δv required to reach its orbit render this object favorable regarding technical feasibility. The properties of 2002 AT4 are listed in Tab. 1.

ii. Sample Requirement

The sample requirements shown below are necessary to achieve the scientific goals. Firstly, besides the surface sample material, subsurface material is required with a sampling depth of 20 cm. This is to obtain material which is not altered by space weathering and impact gardening characteristic of the upper surface layer. Even though regolith depth is an unknown property, we are still able to answer our questions from it. Greater depth would increase the probability of retrieving primitive material mixed together with the regolith, or even the primitive material itself. To guarantee scientific success, several independent measurements are needed as well as having additional samples preserved for future measurements. These requirements need a minimum sample mass of 10 grams. Once the sample is captured, it has to be kept at a suitable temperature to not lose sample information. The maximum temperature requirement for the sample is 313 Kelvin, based on the maximum temperature that alters the organic material.

iii. Instrument requirements

We list the scientific instruments in Table 2, that we have for the orbiter and lander. To fulfill all objectives, we need a sample to analyze the material with the instruments on Earth. The instruments on board the spacecraft are for necessary in-situ measurements as well as for backup measurements.

IV. Sample Analysis and Curation

Upon sample-return to Earth, further analyses will be made to achieve the main scientific objectives. For example, by investigating the chondrules and refractory inclusions in the matrix, the age of the compounds in the sample can be determined, along with the disk dynamics, volatility fractionation, thermal history and accretion dynamics. This is done through analysis of isotopic abundances, mineralogy and mineral chemistry. To achieve this, a selection of high-precision, high spatial resolution instruments are available on earth. One major advantage of bringing the sample back to Earth is also the possibility of using future, improved technology on preserved samples.

The sample will be preserved and protected in a dedicated facility on Earth, adapted to the specific storage requirements of the sample. Here are some examples:

- Extraction and analyses of organic components (amino acids) to understand the origin of life
- Isotopic measurements (O/H) to learn about the chronology, migration of bodies and the evolution of the Solar System
- Mineralogical Characterization to characterize the physical properties of D-type asteroids
- Identification and extraction of presolar grains

If such a facility becomes available by ESA in Europe within the time scales of the mission, this is the preferred option. Otherwise, curation facilities in the USA or Japan will be utilized.

Instruments (Spacecraft)	Scientific requirement	Instrumental requirements	Reference
Wide Angle Camera	SR4, SR11,SR12	Imaging whole asteroid with 50 cm / pixel at 5km distance, FOV : 11.2 deg	[7]
Narrow Angle Camera	SR4,SR12	10 cm/pixel at 5 km distance, FOV: 1.7 deg	[17]
High Frequency Radar	SR4, SR12	Resolution 2 m, penetration: 10 - 20 m, nominal frequ.: 300-800 mHz, external frequ.: 300 - 2500 Mhz	[6]
Low Frequency Range Radar	SR2, SR4, SR12	Resolution 15 - 30 m, penetration depth: 170 m, nominal frequ.: 50-70 mHz, external frequ.: 45 - 75 Mhz	[18]
Mid-Infrared Spectrometer	SR4	Spectral range: 400-2000 cm^-1 with maximum resolution 10 cm^-1	[5]
Visible Near-Infrared Spectrometer	SR4	Wavelength range: 0.4 - 3.3 μm , resolution: 5 nm	[14]
Neutral Particle Analyser	SR10	Mass resolution: H, Heavy energy range: 10 eV to 3 keV	[23]
Instruments (Lander)			
Panoramic Cameras (8)	SR4	Spectral Range: 400 - 1100 nm, FOV: 60 deg	[4]
Descent camera		0.1mm /pixel at 1m distance	[20]
LIBS + Raman	SR1, SR5, SR9, SR12	Spectral resolution of 10 cm^-1, Raman shifts: 4000 cm^-1 - -100 cm^-1	[11]

Table 2: *Instruments on the spacecraft and the lander with their requirements.*

V. MISSION ANALYSIS

i. Launch & Orbit

Low thrust orbit trajectory optimization for primary and secondary targets was performed using basin hopping method, setting objective function to maximize spacecraft mass at asteroid arrival and using Ariane 62 launcher performance curve as an optimisation contraint. Arrival trajectory was optimized using STK Astrogator tool. Optimized orbits use Earth gravity assist for arrival to the asteroid and have a total mission delta v budget of 10.4 to 11.4 km/s, depending on the selected launch opportunities from 2029 to 2034. Re-entry velocities range from 11 to 12 km/s. The required C3 for orbit injection is about 2.7 Km^2/s^2 which would provide 2370 kg of maximum wet mass capability in case of Ariane 62 launch vehicle. This results into approximately 400 kg of mass margin for current baseline design that can be used for rideshare opportunities if not needed.

ii. Landing Approach and Contamination Avoidance Maneuver (LACAM)

The LACAM maneuver is used for landing the scientific payload inside the lander. Since the asteroid on which we will land has a very low albedo, markers will be used as reference points on the surface for optical navigation. These will be released over the landing site, after the first months in which the landing site will be identified. Also, after the first months of gravitational and topographic mapping of the asteroid, the altitude at which the lander has to be released will be established. For the landing maneuver, in order to ensure no contamination of the sampling site, the orbiter will first shut down the engines for entering a coasting phase. Afterwards, the lander will be released and the engines will then fire again to safely return to higher altitudes.

iii. Sampling

The proposed sampling approach is conceptually identical to the one used in the Rosetta mission SD2 drill [27], as the scale of the operations needed share strong similarities.

iv. Re-Entry

The Earth re-entry phase will begin at an altitude of 120 km. In order to design the re-entry capsule, a multi-objective optimisation algorithm (NSGA-II) has been used. During the re-entry phase, a vehicle has to withstand thermal and mechanical loads. Apart from the initial conditions of velocity and flight path angle when entering the upper atmosphere, these loads are strongly affected by the shape and attitude of the vehicle. Reducing the total heat load during the flight has an impact on the total mass of the vehicle since the thermal protection system (TPS) mass will be reduced. In addition to this, the larger the volume of the capsule, the less the payload will be constrained in its dimensions. Hence, volume and heat load are chosen as objective functions. The two objective functions will be optimized by varying four different parameters that define the capsule's shape (see Figure 1). These are the nose radius (R_N), the rear length (L_c), the rear angle (θ_c) and the side radius (R_s). The middle radius is fixed at $R_m = 0.2$ m. The capsule structure and thermal protection system used will be the same of Hayabusa re-entry capsule. Hence, the same maximum g-load and heat flux can be sustained by the capsule (i.e., a maximum g-load of 50 g and a maximum heat flux of 1.5×10^7 W/m^2). By running the optimization (see Figure 2), a Pareto front was found: from there, it was chosen a capsule with a volume of $V = 0.0464$ m^3 and heat load of $Q = 1.9560 \times 10^8$ J/m^2, and the optimal capsule resulted to have the following parameters: $R_N = 0.6998$ m, $L_c = 0.1977$ m, $\theta_C = 3.25$, $R_s = 0.0026$ m; this corresponded to a total volume of

Since the mass of the capsule structure, thermal system and sample container is estimated around 38 kg, and since the entry conditions are similar to the Hayabusa mission, a carbon phenolic thermal protection system is chosen as heat shield. The mass required for this thermal protection system constitutes 30 % of the capsule mass. This means that the whole capsule will have a mass of around 50 kg.

VI. ORBITER

i. Propulsion Subsystem

Due to the large Δv requirements of the mission, electric propulsion would be the propulsion system of choice

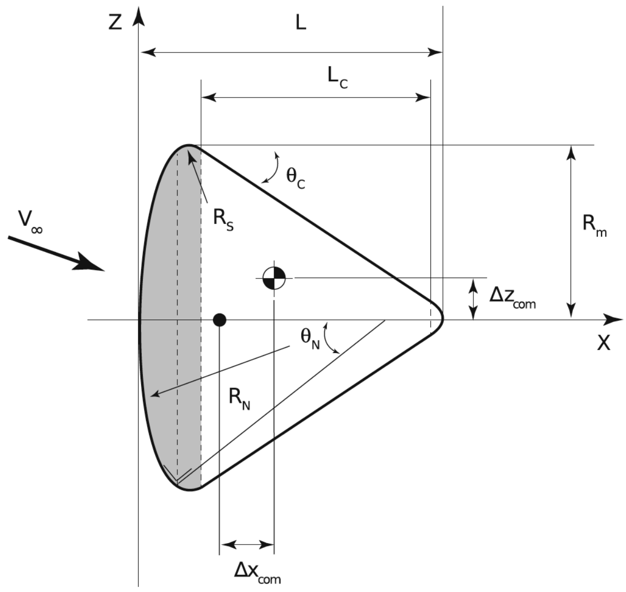

Figure 1: *Re-entry capsule shape parameters [8]*

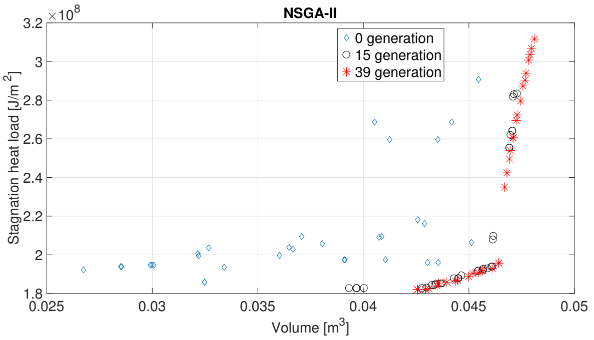

Figure 2: *Optimization results (NSGA-II)*

over a chemical propulsion system. Two candidates are considered, simulated and studied: the T6 ion thruster and the PPS-1350 Hall thruster, two European electric propulsion systems with interesting characteristics and high TRL. The former will be used in BepiColombo and the latter was used in SMART-1.

The main difference between the two thrusters is the power consumption and specific impulse (Isp). Similar to the configuration of BepiColombo, DESIRE would have four thrusters, of which two would be firing at a time. This approach is chosen for redundancy and degradation reasons. The most important values for four engines are noted in Table 3. [1].

For a given ΔV and a dry mass (i.e. excluding the mass of tanks, engines and solar arrays), the required mass of propellant, tanks, engines (fixed), and solar arrays (fixed) to achieve the given Δv can be calculated. Results suggest that for a low amount of dry mass and Δv, the PPS-1350 configuration is less massive (propellant, tanks, engines, solar arrays) than the T6. In the case of DESIRE, simulations show that T6 would be the choice of preference in terms of total mass, as the overall mass would be less than with the PPS-1350.

	T6 ion thruster [24]	**PPS-1350 Hall thruster [2]**
Thrust	290 mN	180 mN
Power	9 kW	3 kW
Isp	4120 s	1650 s
Engine mass	∼130 kg	∼84 kg

Table 3: *Properties of candidate electric thrusters (values for 4 engines).*

Two Xenon tanks of 208 litres each and 20.4 kg are used to store all the required propellant for the mission including a 10 percent margin.

ii. Attitude and Orbit Control System (AOCS)

Two different AOCS will be mounted: one for the orbiter and one for the lander. The orbiter will be three axis stabilized and its AOCS will consist of sixteen 1N hydrazine thrusters for large attitude maneuvers and reaction wheels desaturation, twelve needed for controlling the attitude of the orbiter, while four are used for redundancy. Also, it will be equipped with four reaction wheels which will allow fine attitude maneuvers. Furthermore, optical cameras are used for the navigation relative to the asteroid, together with laser altimeters to determine the relative distance. Finally, two star trackers, four sun sensors and three inertial measurement units will be used to determine the state of the spacecraft.

iii. Thermal Control System (TCS)

The system is able to regulate the temperature of both the spacecraft interior (278K), and the sample canister (263K) during the cruise and reentry phases.

These temperatures come from the scientific requirement of preserving the organic traces of the sample. The sample has to be kept below 313K during the whole cruise back. Apart from that, all the instruments and subsystems present on the spacecraft have an operational temperature range that must be taken into account. Some of them such as batteries or propulsion subsystems (e.g. hydrazine) have a narrow range (268K to 293K and 278K to 313K, respectively), while others have a larger margin, like solar arrays or antennas (122K to 373K and 173K to 373K).

All in all, the chosen configuration for the TCS of the spacecraft is based on a louvre mechanism to get heat flux from the Sun, which will be the main source of heat. This can be closed during the shadow period of operation and therefore reducing the heat losses. A radiator will be installed to eject the heat reflux from the electric propulsion system (≈5000 W) and other subsystem to the space environment. This whole arrangement will be connected by a Loop Heat Pipe (LHP) to carry the heat loads within the system.

Apart from that, surface coating and Multi-Layer Insulation (MLI) are used to maximize the solar flux performance on the spacecraft.

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[1] `https://directory.eoportal.org/web/eoportal/satellite-missions/r/rosetta`, accessed: 2018-07-25

The main source of power (200 W) and mass (33 kg) budget of the TCS is being conducted by the heaters, which will be used to keep the instruments in their operational temperature ranges.

As regards to the lander section of the spacecraft, the drill doesn't need to be cooled down, as the rotation speed is of the order of few millimeters per day. However, other instruments do need to be heated up by the use of conduction paths and heaters.

The most challenging part of the TCS design is the Sample Re-entry Capsule and the trip back from the asteroid. Our proposal is based on the one used by [16] and [28]. It consists on a two-phase aerogel radiation isolation and Phase Change Material (PCM) around the sample canister, which will be surrounded by an RF beacon to prevent contamination. The system will count with an active cooling system that will maintain the sample canister at an optimal temperature of 263K.

iv. Electrical Power System (EPS)

The power system is one of the most important systems we have. Without energy we cannot operate missions in orbit. For generating energy this missions takes solar cells, due to the fact that they are not complex and are used often in satellites. As it can always occur that the solar cells are not working properly, rechargeable batteries (also called *secondary batteries*) have to be be integrated. The batteries have to be sized so that the important devices will also work when no electricity is being generated by the solar cells.

v. On-Board Computer (OBC)

The On-Board Computer will include two redundant flight-proven LEON3-FT Central Processing Units (CPUs) for data processing, housekeeping, telemetry, tracking and commanding [9]. The data is stored on Solid State Mass Memory (SSMM) with additional storage on Random Access Memory (RAM) and on payload instruments. The SSMM of the spacecraft will include 200 GBit of storage and the lander will have 10 Gbit of storage. Software infrastructure SCOS 2000 will be used, which has been flight proven on multiple missions [22].

vi. Telemetry, Tracking & Commanding (TT&C)

For large data transfer both X-band (8.5 GHz, ESA) and Ka-band (32 GHz, ESA) were considered [10]. Rain attenuation would be an important consideration in frequencies above 10 Ghz. For Ka-band the elevation angle of the antenna should not be over 20 degrees [29]. The requirement would severely limit the amount of data that could be transfered and as such X-band was chosen. The gimbaled 2.2 m high-gain parabolic antenna of Rosetta would be used. The requirement for the data rate is 0.21 Mbit/s. From the calculations it was found the transmitter should have a transmitting power of 200 W. For telemetry between the spacecraft and the lander and as a backup a medium-gain S-band (2 GHz) antenna of Rosetta will be used. For commanding, housekeeping and as a backup two low-gain 2 GHz antennas of Rosetta will be used. Both systems will be also present on the lander.

vii. Canister Capture Subsystem (CCS)

For capturing samples returned to the orbiter, a funnel and arm system on the orbiter will be used. The system has already been tested in a zero-gravity environment, in the context of the ESA Study "Sample Canister Capture Mechanism (SCCM) Design and Breadboard" [19]. The principle of operation will be as follows: the samples will be retrieved by the lander and put in three different canisters which are then placed on a moving platform. A screw allows the canister to be pushed upwards and released at a certain velocity which will be set depending on the gravity measurements taken by the orbiter. Three canisters are provided for redundancy: if one canister is not caught by the orbiter, there will still be two other canisters available for subsequent attempts. The moving platform will allow the canister to reach a velocity in the range of 5 cm/s to 20 cm/s, which will be set more precisely once in-situ gravity measurements are acquired. The platform will push towards the canister out of a slot in the lander and towards the orbiter hovering an appropriate height overhead. The canister will be ejected at a speed greater than the escape velocity of the asteroid, ensuring that it does not crash into the surface if it is not caught by the orbiter. In this case, the canister would be on a heliocentric orbit very similar to that of the asteroid, meaning the orbiter must use only a small amount of Δv to catch up and retrieve the canister. The funnel is provided of a robotic arm which will be equipped with optical sensors: once the canister enters the funnel, the robotic arm is rotated preventing the canister to escape from the funnel.

VII. Lander

Landing on small bodies with very low gravity, like asteroid, is principally very different to landing on a planet or moons. With the given target and the suggested descent strategy found in this report, a very low impact velocity is expected. At such low speeds, bouncing is a significant issue. Due to the low gravity and the nature of the drilling operations to be performed, anchoring should be ensured.[26] Our lander, called GALA (Gently Arriving and Landing on an Asteroid), will touch down at a low speed and will use a variety of systems to ensure it stays attached to the surface.

Due to similarities with the expected target body, it is suggested to use an adapted approach to that of the Rosetta mission's Philae lander, building on the experiences from this mission to reduce cost, development time and the probability of a failure.

i. Impact handling and bouncing prevention

In the case of Philae, neither of the two harpoons nor the cold gas thruster fired to hold the lander against the

Subsystem	Mass [kg]	Power [W]
Propulsion (+5%)	171	9450
AOCS (+5%)	137	53
Thermal (+5%)	91	300
Arrays and batteries (+5%)	245	-
Payload (+20%)	27	194
Telecom (+5%)	95	231
Structure and other (+10%)	356	58
Lander (+20%)	146	258
Propellant (+10%)	520	-
Total (+20%)	**1958**	**12343**

Table 4: *A compressed version of the mass and power budget*

comet, despite the telecommand for their firing having been received by Philae.

Failure analysis of the harpoons suggested that they failed because of the ignition. An identical harpoon that was stored in a thermal vacuum chamber also failed, suggesting that the thermal and vacuum environments may also have been significant factors.

Furthermore, the cold gas thruster intended to push the lander to the ground never ignited. Cold gas thrusters can be considerd to have a high TRL, although the cold gas thruster used on Philae had to be custom made due to sizing constraints.[27] To ensure the highest possible TRL for mission components, systems with flight heritage will be used wherever possible, including the cold gas thrusters for pushing the lander towards the ground.

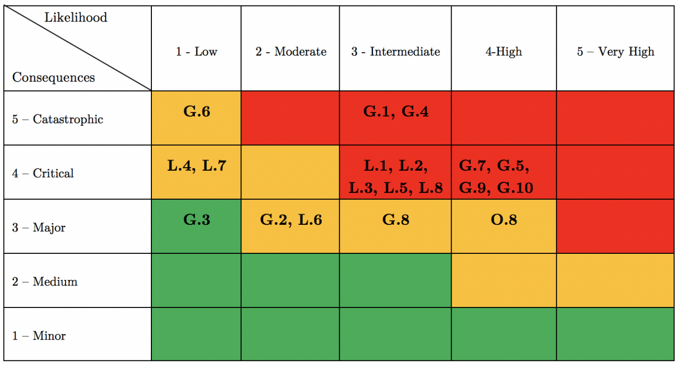
To ensure that the failures of Philae are avoided, the concept and systems of the GALA lander will be thoroughly tested. Lessons learned from Philae, particularly regarding the harpoons and cold gas thruster, will also be integrated into our design. In particular, three harpoons instead of two will be used, and each harpoon will be provided sigh two pyrotechnical gas generators. Each of these will be made of different pyrotechnical materials provided with two separate gas chambers. Also two different types of propellants will be used, and the chambers will be sealed instead of screwed.

VIII. OPERATIONS & GROUND SEGMENT

The mission will be mostly operated from 3 ESA Tracking Stations (ESTRACK) in Argentina, Spain and Australia. The transmission will be carried out by 35 metre diameter X-band (8.5 GHz) parabolic antennas. For backup, 6 parabolic antennas (<15 metre diameter) of the core network or augmented and cooperative network could be used [10].

IX. COST AND RISK ANALYSIS

A compressed version of the mass and power budget represented in table 4. A similar approach was taken to calculate the mass and power budget of the lander, which had a total mass and power usage of 146 kg and 283 Watts respectively



Likelihood Consequences	1 - Low	2 - Moderate	3 - Intermediate	4-High	5 – Very High
5 – Catastrophic	🟨 G.6	🟥	🟥 G.1, G.4	🟥	🟥
4 – Critical	🟨 L.4, L.7	🟨	🟥 L.1, L.2, L.3, L.5, L.8	🟥 G.7, G.5, G.9, G.10	🟥
3 – Major	🟩 G.3	🟨 G.2, L.6	🟨 G.8	🟨 O.8	🟥
2 – Medium	🟩	🟩	🟩	🟨	🟨
1 – Minor	🟩	🟩	🟩	🟩	🟩

Figure 3: *Risk map before mitigation*

i. Cost

In order to achieve a good cost estimate, the mission is compared to other similar missions like the Marco Polo proposals and Rosetta mission according to similarities and differences, in order to estimate costs. We astimated the costs of *DESIRE*-mission in the following categories:

1. Launch (Ariane 62): 75 M EUR
2. Industrial costs: 810 M EUR
3. Mission and Science Operations Centres costs: 154 M EUR
4. Payload: 83 M EUR
5. Contingency: 195 M EUR

Summing these, a minimum budget of 1.496 B EUR is required.

ii. Risk

The risks identified were divided into 3 categories: general risks, orbiter risks and lander risks. The risk map before mitigation is shown in Figure 3. The mitigation strategies have been divided into three categories: mitigate (i.e. the risk is mitigated by executing certain actions), research (i.e. more studies are needed before establishing the types of measures to be taken for mitigating the risk), accept (i.e. the consequences and/or probability of the risk are so low that the risk is accepted).

The identifiers in the figure refer to the following risks:

G.1 Launch Date is missed. *Mitigation*: backup date.

G.2 Targeted Asteroid is changed due to new evidence. *Mitigation*: backup target.

G.3 Collisions with space debris. *Mitigation*: accepted.

G.4 Thrusters failure. *Mitigation*: redundancy of thrusters.

G.5 Re-entry aerodynamic and thermodynamics loads exceeded. *Mitigation*: entry flight path angle and velocity are chosen including safe margins.

G.6 Launcher failure. *Mitigation*: accepted.

G.7 The asteroid is not detected. *Mitigation*: spacecraft equipped with wide angle camera.

G.8 The capsule design fails the flight and wind tunnel tests and cannot be developed. *Mitigation*: research and backup solutions.

G.9 Development risk of the drill. *Mitigation*: research.

G.10 Development risk of the sample retrieval mechanism. *Mitigation*: research.

O.1 The orbiter contaminates the samples using the thrusters. *Mitigation*: cold gas thrusters.

L.1 The lander does not land properly. *Mitigation*: fly wheel, mapping of the surface and determination of release height.

L.2 Sample return platform does not work accurately enough. *Mitigation*: research.

L.3 Harpoons fail to penetrate the surface. *Mitigation*: commercial-off-the-shelf nitrogen thrusters to push the spacecraft down.

L.4 Detachment of lander's legs fail. *Mitigation*: accepted.

L.5 Drill does not manage to go inside the surface. *Mitigation*: drilling mechanism can move within a circumference of 1 m diameter.

L.6 Carousel mechanism does not work properly. *Mitigation*: research.

L.7 Solar cells do not work properly. *Mitigation*: accepted.

L.8 Development risk of the new anchoring system used for freeing the harpoons. *Mitigation*: research.

iii. Descoping options

For a space mission many safety margins are usually taken into account. This section analyses the instruments that could be removed from the spacecraft in case of any shortage of power, mass, volume or monetary budget.

The first item to be eliminated would be the student experiment, as is not one of the primary scientific goals of the mission. The same logic is applied to the NPA, the HFR, the LFR, the MIR and the NIR (scientific analysis of the target is not the main scientific requirement). Also, both the Panoramic Camera and the Descent Camera could be eliminated, as the geological context of the drilling site would not be lost.

In the engineering part, redundancy of most of the systems may be avoided if necessary, as well as the margins for heat conduction mechanisms and propellant tanks.

X. Public Outreach

To increase mission engagement with the general public, the lander will have room for an extra instrument, proposals for which will be submitted by members of the public. This will include students, so will give them a unique opportunity to take part in real space science and engineering and to be at the cutting edge of their field.

XI. Conclusions

Earlier mission proposals regarding sample return from asteroids have lost to other proposals. The repeated proposals of Marco Polo missions, as well as the recent activities of NASA and JAXA, indicates that these are interesting questions to the scientific community. By using the heritage from missions such as Rosetta, ESA should be able to visit a D-type Asteroid with reasonable cost and with a large amount of scientific return.

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