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20'000 Leagues Below the Ice: Enceladus Life Explorator (E.L.E.)

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Abstract

The ELE spacecraft will arrive to Saturn in fall 2047, 12 years after its launch, and begin a 2 year orbit around the planet, encompassing 10 flybys through the south polar jets of Enceladus. Returning samples from this moon will provide answers to many questions about geological activity in icy worlds, potential habitability and maybe extraterrestrial life. This article provides a review of the spacecraft design. The major engineering functions of mechanical configuration, power generation and distribution, propulsion, telecommunications, trajectory, and some other design features are discussed.
Keywords: Interplanetary Trajectory, Sampling system, Biocontainer-cryostat, Search for Life

Nomenclature

Δv: global impulse; I_{sp}: specific impulse; v_e: exit velocity; g: gravitational acceleration; M_0/M_f: initial/final mass; Δm: mass variation; F: force

Acronyms/Abbreviations

S/C: spacecraft
ELE: Enceladus Life Exploratior
ELF: Enceladus Life Finder
ULA: United Launch Alliance
GTO: Geostationary Transfer Orbit
LEO: Low Earth Orbit
EOL: End of Life
OWLS: Oceans Worlds Life Surveyor
PCM: Phase Change Material
NTO/MMH: Nitrogen-Tetroxide / Monomethyl-Hydrozine
JPL: NASA Jet Propulsion Laboratory
OCEANS: Organic Capillary Electrophoresis Analysis System
ELVIS: Extant Life Volumetric Imaging System
GPHS-RTG: General Purpose Heat Source – Radioisotope Thermoelectric Generator
AOCS: Attitude and Orbit Control System
CDH: Command and Data Handling System
IMU: Inertial Measurement Unit
DSN: Deep Space Network
LGA/MGA/HGA: Low/Medium/High Gain Antenna

1. Introduction

The quest to uncover the mysteries of our solar system and explore the possibility of extraterrestrial life fuels scientific curiosity. Central to this pursuit, and this mission, is the fundamental question: does life exist beyond Earth? This inquiry is at the origin of the exploration of various celestial bodies, guided by the premise that life, as we understand it, necessitates the presence of liquid water. Enceladus, Saturn's icy moon, in addition to having one of the brightest and youngest surfaces, is a prominent candidate for hosting life, as we also recently found phosphorus, rarest ingredient for life, coming from its sub-surface ocean.

At the root of all the questions around this moon is the Cassini-Huygens mission, which unveiled the presence of a plume emanating from its south pole, consisting of numerous geysers or jets. High-resolution observations disclosed that the liquid reservoir supplying these eruptions exists not near the surface but deeper within the moon, offering a unique opportunity for direct sampling in the plume, as it provides insights into the composition of the ocean. The Cassini Orbiter, through in situ measurements using low-resolution mass spectrometers, has demonstrated the feasibility and motivation for such method.

In addition, the discovery of organic and nitrogen-bearing molecules in the plume vapor, along with the detection of salts in the plume's icy grains, reinforced the argument for water in contact with a rocky core.

While Cassini laid the foundation, it could not definitively confirm the presence of an active biota in Enceladus' ocean or provide detailed information on crucial environmental factors.

Enter Enceladus Life Explorator (ELE), its logical successor. This mission is adapted to traverse the plume of Enceladus multiple times, and aims to investigate the primordial sources of organics, sites of organic synthesis, and the potential presence of habitats beyond Earth that harbor conditions suitable for life. Equipped with new technologies, ELE surpasses Cassini in terms of mass range, resolution and sensitivity of compositional instruments. The simplicity and robustness of sample collection and processing enable ELE to comprehensively reveal the composition of Enceladus's plume.

2. Mission statement

2.1 Goals

ELE mission goal is to investigate Enceladus's south polar jets and collect some data thrown out in space and analyse their composition. As the main objective, the probe will also come back with some samples for further analyzes on Earth.

The mission aims to confirm the presence of an active biota in Enceladus's ocean and provide detailed information on essential environmental parameters, including pH levels, redox state, available free energy, and temperature.

2.2 Mission & Science Objectives

ELE's scientific objectives are divided in three key areas. First, it seeks to determine whether the organics and volatiles from Enceladus have undergone thermal alterations over time, to verify the theory of an hydrothermal circulation and convecting ice at the center of the moon. Second, it aims to characterize the interior marine environment by examining pH, oxidation state, available chemical energy, and temperature, crucial for assessing its life-carrying capacity. Third, the mission conducts chemical measurements to identify indications that organics may result from biological processes, employing three types of measurements recognized as diagnostic of life.

2.3 Stakeholders & Actors

The main stakeholders and actors (as figure 1 shows) would be the congress (include in the government), international collaborations as NASA, private companies as ULA for the launch, the Department of Defense which promotes space exploration and development, through lobbying efforts, educational programs, and public awareness, and finally the general public.

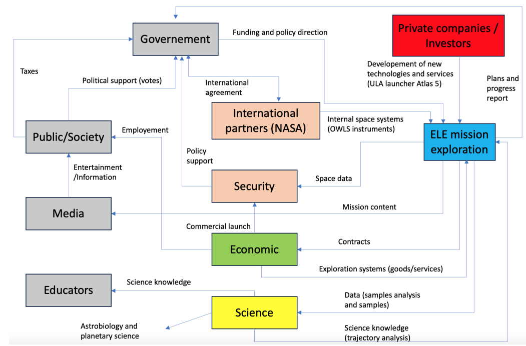

Fig. 1: Stakeholder value network diagram for the mission

Source: [1]

3. Mission design

3.1 Mission design & CONOPs

ELE mission plays on simplicity and efficiency, as it will just go through the plume of Enceladus to collect data directly in space, thrown out by Enceladus geysers. They are free samples, so no need to dig or drill.

The mission requires the collection of 5 samples to bring back to Earth (another sample for in situ analyzes), a redundancy needed as some of them could in the worst case scenario be non insightful or ruined. It gives a total volume of around: $V_{samples} = 5\times 20 = 100cm^3$. Knowing that Enceladus density is of $\rho_{enceladus} = 1.6g/cm^3$, we deduce that one sample will contain a mass of 32 g, and we calculate the mass of pure solid samples: $m_{solid} = 160g$. Thus we can deduce that with an unknown density of gas and grains in the plume, the total samples mass won't exceed 160 g. Adding the mass of the containings (we assume that it's 1 kg each), we obtain a mass of 5.16 kg which is negligible compared to the rest of the spacecraft.

3.2 Potential launch windows

3.2.1 Global impulse Δv and travel duration

With the help of the study on Earth-Jupiter-Saturn interplanetary trajectory in the article [3], we get the first optimized trajectory, which is using Jupiter, doing a close flyby to get an additional Δv of 0.36 km/s, it's called a gravity assist. The total global impulse is of 7.4 km/s, starting from LEO. As we start from GTO, it reduces to 4.6 km/s. With a margin of 20% for our calculations, we find that $\Delta v_{tot} = 5.4$ km/s. The second optimized trajectory consists of a pure flybly, so the gravity assist doesn't have any impact on the Δv. The total global impulse is about 8.7 km/s, starting from LEO.

The time and dates for take off, indicated in the figure

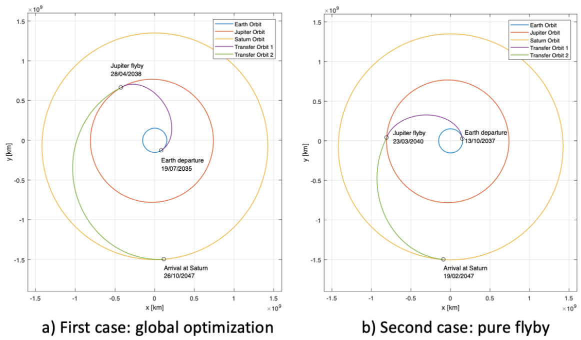

Fig. 2: Two possible trajectories with different timelines for the going

Source: [3]

2, are different for both cases. In the first case, the S/C takes off in the middle of 2035, passes by Jupiter in 2038 to arrive to Saturn in fall 2047. The travel time is around 12 years. In the second one, the launch takes place two years later in fall 2037, to arrive in the same year as in the first case.

The second optimized trajectory has the advantage of reducing the time of travel by 2 years, but needs an additional global impulse of 1.3 km/s compared to the first one. As we will need more energy, so more mass for the propulsion (both chemical and electrical propulsion), we will chose preferably the less energy consuming trajectory, so the first one.

3.2.2 Launch windows

A launch is possible every 11-12 months, during approximately 5 years: interval [2034-2038]. But the trajectories and Δv are optimized for the cases studied before.

3.3 Mission phases and timeline

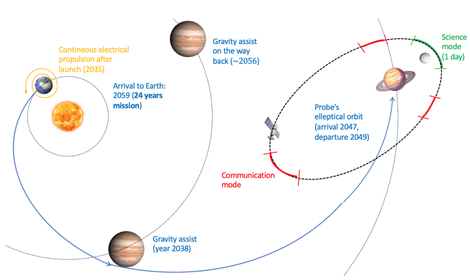

Fig. 3: Trajectories and orbit of the mission

Source: [2]

The S/C is planed on being sent by Atlas 5 (551) to GTO orbit, in the launch site of Cape Canaveral SLC-41. This launcher can send a maximum mass of 10300 kg to the orbit wanted.

After the separation of the launcher, electrical thrusters takes over to escape earth gravity in spiral, as shown in figure 3. This operation mainly consists of a continuous thrust, giving a global impulse of around 1 km/s.

The trajectory (Δv and timeline in precedent part) as indicated includes a gravity assist using Jupiter, and the flyby has its closest approach attaining 205871 km of altitude. It necessitates small maneuvers.

As the S/C arrives to Saturn, it enters an elliptical orbit. During 2 years, as explained by [2], there will be 10 flybys at 5 km/s each, and a 62 days orbit that allows ample time to set instrument parameters for the next flyby. The S/C takes some samples at each flyby, analyse it and send results to Earth (takes back 5 samples). Flybys will be done at an altitude of around 50-100 km at 89 degrees S latitude.

The way back have the same trajectory and gravity assist as for the going as the alignment of the planets will permit it, so the necessary Δv will be the same. We take the assumption that the return will take about 10 years. So in total, the mission should last around 24 years.

3.4 System modes

The mode re-bout is always activated after the launch in case that a problem (interferences, magnetic wave or radiation) shuts down a subsystem of the S/C.

Everything is turned off during the launch phase, and the communications and propulsion subsystems activates just after the end of this phase.

Some scientific equipment (mainly, OWLS, sampling system) are turned off until the S/C arrives to Enceladus (equipment prepared before the flyby).

During the elliptical orbit around Saturn, there will be principally one science mode (OWLS + sampling) of one day during the flyby (and after to analyse data) and 3 communication modes to send the results and control the S/C (figure 3). Some propulsion modes are planed to make maneuvers and stay in orbit. Also, other periods during the orbit is consecrated to the study of Saturn and Enceladus using the other scientific instruments (radar, camera, radio-science).

3.5 EOL strategy

The goal of the mission is to come back to Earth with some samples. To achieve it, it is not obligatory that the S/C comes back in one piece: scientific equipment, or other types of equipment are not needed anymore for the way back, thus we can make the assumption that around 500 kg of materials will be thrown into Saturn and disintegrated. The S/C will basically only be composed of the samples, the propulsion and navigation part, and the communication part.

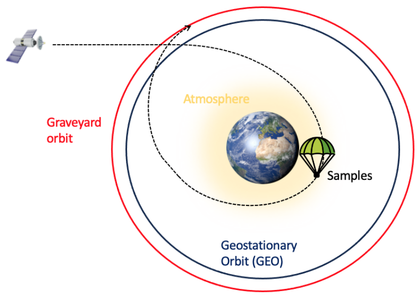

Fig. 4: Trajectory of the spacecraft at its return to Earth to drop the samples and go to graveyard orbit

Coming back to Earth as illustrated on figure 4, the S/C will use the Earth atmosphere to slow down, at the same time drop on Earth the samples equipped with a parachute, and finish it's trajectory on the graveyard orbit to end its life. This last maneuver will be helped with some electrical thrusts, in sufficient quantity due to the small final weight of the S/C (nearly all the fuel consumed, without scientific equipment). For the EOL strategy, we didn't opt for a re-entry in Earth atmosphere to burn it, to reduce the risk of releasing radioactivity on Earth with the RTGs.

The mission is listed «Category V» according to the Cospar Planetary protection policy.

4. Systems engineering

4.1 Functional analysis

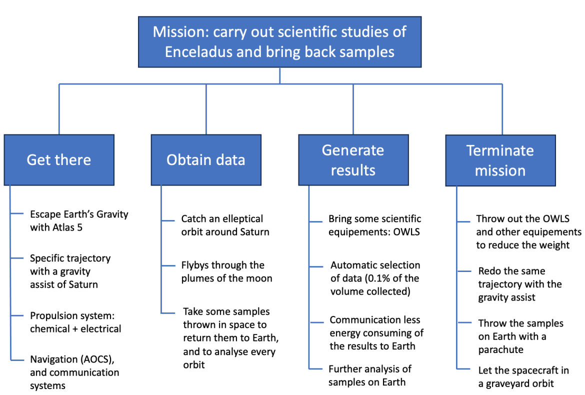

Fig. 5: Functional tree of the mission

4.2 Mission requirements

Firstly, the mission needs a trajectory that is carefully respected during the elliptical orbit around Saturn, to be sure to pass through the plume: an exact inclination is primordial to collect data.

The samples must be preserved and secured by the capsule, equipped parachute, so that our scientists will receive them intact after entering Earth atmosphere at high speed and landing. A radio antenna is also required for accurate location to ensure a quick retrieval.

The mission needs good functionality of the scientific equipment to get data, and robust communication with Earth to send the results.

Enough energy production is needed for the electrical subsystems (control computer, ion thrusters, valves, ...), and enough mass of propellant for the propulsion part. Also, enough data storage for the collected data and results, and a good use of the battery.

To have a good control of the S/C, we need a good orientation of the antenna to receive the signals in a moderate rate. The attitude controllers should work well, so redundancy of some equipment is needed.

The RTG and the propulsion part of the S/C should be thermally isolated from the rest of the spacecraft.

Due to the rather checkered safety record of the Li/SO2 system, safety has been foremost among the design considerations and has been addressed at the cell, battery and system level.

4.3 Mission constraints and limitations

The first constraint we are facing concerns the probe's orbit around Saturn: an orbit around Enceladus was considered but would be too difficult, because of multiple reasons. The main one is the high additional mass of propellant that it would take to enter the orbit, and escape it (additional Δv). Also, it would imply a lot of thrusts to maintain the same orbit (rely on station-keeping maneuvers), due to the giant gravity of Saturn next door. Thus, the land of a rover would be too complicated as it would arrive at high speed from our chosen orbit.

Some others are limitations of time, like the launch time constraint as the first launch is more attractive for us, or building a miniaturized version of the OWLS before launch. Also, the time into the plume is limited as it is colder in this zone, as the time to close to Saturn because of radiations.

Finally, we have a constraint linked to flybys' altitudes, because the density in the plume, to collect the samples, is smaller as we are moving away from the moon.

4.4 Measures of effectiveness

The mission will succeed if:

- The S/C has enough propellant to come back to Earth with the wanted samples.

- The samples are intact and are full of insightful information to be studied.

- The quantity of nitrogen indicates a volatile evolution on Enceladus (thermal activity) and the ocean of Enceladus satisfies the basic requirements of habitability. An additional and prominent reason of success, although less likely, is that the plume of Enceladus contains chemical signatures of biology.

4.5 Interfaces analysis

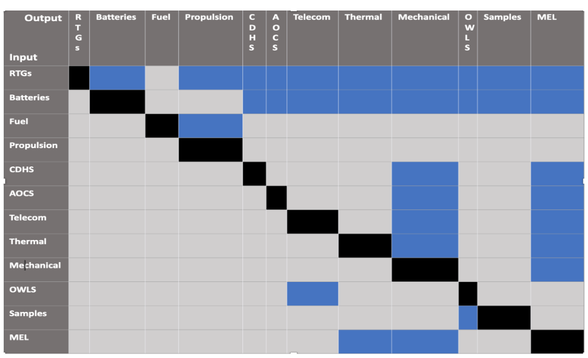

Fig. 6: Design Structure Matrix (DSM) for the S/C

5. Mission architecture

5.1 Alternative conceptual solutions

The ELE mission is taking advantage of the heritage of the Cassini-Huygens mission, which is at the origin of all the question around Enceladus. The same telecommunication principle is used, as well as the same overall structure configuration.

In addition, the mission was designed as the ELF mission, a proposed mission concept for a NASA S/C that intended to assess the habitability of the moon. Thus the same scientific objectives were taken, and the same strategy in term of collecting the data, consisting of passing through the plume using the same elliptical orbit around Saturn.

5.2 System budgets

For this part, we will use the rocket equation:

$$\Delta v = I_{sp} g ln(\frac{M_0}{M_f}) = v_e ln(\frac{M_0}{M_f})$$

We calculated the Δv before (5.4 km/s from GTO). We assumed the same trajectory on the way back, thus the same Δv, which has the following distribution (figure 7):

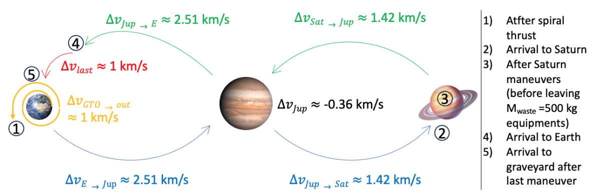

Fig. 7: Distribution diagram of the Δv along the going and the way back

As only small maneuvers will be done around Jupiter for the flyby, the Δm of xenon used is negligeable in the calculations, thus the rocket equation can be used during the phases 1 to 2 and 3 to 4.

We have a S/C mass of $M_{wet} = 8120kg$ at the start of the mission, which has the following global equation decomposition:

$$\begin{aligned} M_{wet} &= M_{dry} + M_{waste} + M_{bp,2} + M_{bp,4} \\ &\quad + M_{x,1} + M_{x,3} + M_{x,5} \\ &= M_{dry} + M_{waste} + M_{bp} + M_x \end{aligned}$$

where $M_{bp,i}$ and $M_{x,j}$ are respectively the mass of bi-propellant and xenon used during the precedent phase to get to i (respectively j). Using the rocket equation between each phase (Δv used to get from precedent phase to the current one in km/s and masses in kg):

Phase nb:	1	2	3	4	5
Δv	1	4.15	0.5	4.15	0.5-1
S/C mass	7925	2166	1650	451	440
Propulsion	Elect.	Chemic.	Elect.	Chemic.	Elect.
Fuel mass	195	5759	26	1199	11

Thus the S/C needs a bi-propellant mass of $M_{bp} = 6958kg$ and a xenon mass of $M_x = 232kg$. Counting that a equipment mass of M_{waste} is thrown to Saturn before coming back, we conclude that the dry mass is about $M_{dry} = 940kg$.

Parts	Actual mass
Structure	250 kg
Thermal	85 kg
Telecom	70 kg
CDH	20 kg
AOCS	30 kg
Propulsion	45 kg
Power	181 kg
Payload	166 kg
Total Dry Mass +10% margin	931.7 kg

In the precedent table, we have verified that the actual S/C dry mass is in the range of the one found.

5.3 Risk analysis

Risk	Likelihood	Impact	Mitigations
Loss and/or damage of samples capsule	2	5	Cryocooling system to keep the sample cool, drag chutes to decelerate the capsule during reentry, radio antenna to locate, thermally isolated with thick TPS layer of PICA X
Collision/dammage on some mission critical elements (antennas, RTGs), or non functionality of equipment (AOCS)	3	4	Mechanisms to protect/close them, and send multiple of the same equipment for some (redundancy)
Debris collision with the S/C during EOL strategy (as it's getting closer to Earth, it crosses used orbits)	1	3	We need to have a pre define trajectory, moving in the same direction of rotation of debris/satellite in their orbit so that it's easier to dodge.
Delays in the development of critical technologies (OWLS, sampling system)	1	4	Accelerated development program prior to every phase
The plume density is lower than anticipated, impacting the quality and overall usability of the samples.	2	3	Use high precision imaging to assess the plume behavior as it propagates away from the moon

Fig. 8: Risk assessment of some hazards of the mission

A total of 5 risks have been identified for mitigation, related to delays in development of critical technologies, failure of mission critical elements or sampling calculations (figure 8).

6. Baseline Design

6.1 Payload components

The main scientific component of the mission is the OWLS instrumentation suite, developed at NASA's Jet Propulsion Laboratory with a primary focus on "Search for Life" missions in deep space [4]. It's a powerful tool that features eight automated instruments. OWLS combines chemical analysis instruments for detecting life's building blocks, alongside microscopes dedicated to cell identification. The version in figure 9 will be miniaturized and customized for deployment in forthcoming space missions like ours. Given the data generated by these subsystems, only a small estimated 0.0001% can be transmitted back to Earth due to limitations in data transmission rates. To overcome this challenge, OWLS incorporates "onboard science instrument autonomy" through 2 systems named OCEANS and ELVIS. This innovative approach allows the instrument suite to autonomously summarize and prioritize data from the different parts, employing adjustable algorithms. Then the scientists, bringing together multiple overlapping lines of evidence, can optimize their ability to draw robust conclusions regarding the potential existence of life. OWLS has a mass of around 100 kg and a power consumption of 250 W.

Fig. 9: Picture of OWLS

Source: [4]

As Cassini used on its orbiter [8], the Radio-Science subsystem, an integral experiment within the the mission, operates by utilizing the S/C's HGA to transmit radio signals to Earth. During its journey, they interact with various elements of Saturn system, including Enceladus. Upon reaching Earth, scientists analyze the altered signals, providing valuable insights into gravity fields, atmospheric composition, surface properties and more. This unique subsystem serves as an observational instrument and is the only experiment where data can be observed in real time. Employing two distinct wavelengths of radio waves - X and Ka band - the signal is sent to the NASA DSN.

As Juice mission [10], we will use a high resolution camera, JANUS: it's an optical camera designed to study the global, regional, and local morphology and processes on the moon and the Jupiter environment. Equipped with 13 filters, JANUS features a 1.3-degree field of view and achieves a spatial resolution of up to 2.4 meters on Enceladus, and approximately 10 kilometers on Jupiter.

Finally, a radar will be used during the mission, as done for Cassini mission [9]. It will be employed to penetrate Enceladus' (and Saturn) environment: by emitting radio waves towards the moon's surface and analyzing the reflected signals, the radar will generate detailed images of the terrain, unveiling hidden features such as surface composition, roughness, and potential geological formations.

6.2 Samples capsule

To ensure the preservation of the samples, they will be collected during the final flyby. A Biocontainer-cryostat design has been proposed by [7] for the Earth Return Capsule and ensures reliable sample preservation. The S/C utilizes effective thermal insulation, passive cooling radiators, and an active cooling system with nitrogen stirling cryocoolers (80K, 1.5W of total cooling power, 120W peak power supply). The Biocontainer, pressurized with 40Ar, prevents sample melting during collection, while PCM serves as a heat accumulator during the return flight. Calculations show the PCM's capacity to secure samples during re-entry, with additional consideration for a heat shield during this phase.

The reentry capsule requires a large design to house the biocontainer and cryocooling system. It contains drag chutes to decelerate the capsule during reentry, and a radio antenna will be located on top of the capsule for accurate location and quick retrieval. Also, there is a 64 mm thick TPS layer of PICA X, selected to withstand the peak heat flux of $1400 W/cm^2$.

6.3 Spacecraft configuration

The S/C subsystems are located as shown in figure 10. The equipment in green is thrown on Saturn before returning, the subsystem in red is thrown on earth at the end of the mission and the rest is going in graveyard orbit at EOL.

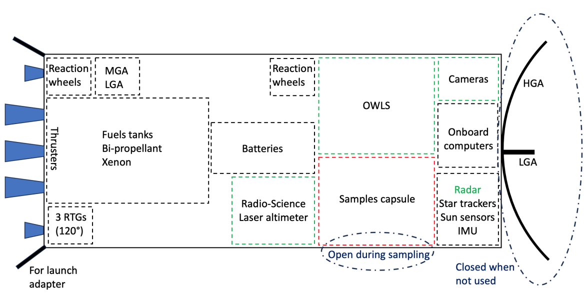

Fig. 10: Diagram of the S/C configuration

During the launch phase every subsystems are closed but during Enceladus flybys, the sampling system is opened and the parabol and communications part are closed and unused. During the studies mode, all the scientific equipment is used and some as the radar and the cameras are deployed. During the communication modes, the parabola is deployed, and the reaction wheels and the electrical propulsion helps to send a signal to Earth.

Finally, the disposition allows the samples to be far from the RTG's and the propulsion part to not alter its temperature.

6.4 Electrical power

The idea of using solar panels to powered the mission was quickly dismissed. Indeed, it would imply to use huge ones, thus adding more mass to the spacecraft, as the light is approximately 100 times weaker near Saturn than on Earth.

We opted for 3 GPHS-RTG, static nuclear sources turning thermal energy into electricity. Its advantage is that its electrical production is independent of the sun and unaffected by the S/C orientation and shadows, so it's commonly used for deep space missions. It provides 30 V DC for scientific instruments, heaters, communication equipment, computer, valves, reaction wheels, radar, camera, Biocontainer, etc., and all this equipment needs an electrical power of 924.84 (770.7 with 20% margin to take into account all the equipment). In this calculation we assumed that OWLS, the radar and radio-science consume the same amount than for Cassini mission [5]. We can assume that we find the mean power consumption P_{mean} by multiplying this amount by 2/3 because not all the equipments are used simultaneously: $P_{mean} = 617W$. Knowing that one RTG produce 295 W, so a total power production of 885 W, we can conclude that the power system will be functional, even at the end of the mission: in Cassini mission, the power production decreased to 630 W, which still works. The 3 RTGs add a total mass of 171 kg (57 each) and a total volume of 3.84 m^3.

The S/C should also possess 5 $LiSO_2$ Saft batteries for a total volume and mass of 0.07 m^3 and 10 kg to store 1600 Wh. Those can supply about 250 W of power for 3 hours operations. This capacity is highly needed for the first electrical propulsion phase (spiral continuous thrust), as the ion thrusters need 500 W each. So by having full batteries at the beginning, the S/C can start the operation by using the two thrusters without any problem. If the duration exceeds 3 hours, we can use them non simultaneously, or do some breaks to refill the batteries.

6.5 Propulsion

6.5.1 Thrusters and propellant definition

The chemical fuel chosen is the bi-propellant NTO/MMH, used with thrusters capable of producing a force of 216 N [11]. The exit velocity ($v_e = I_{sp} g$) is about 3199.31 m/s and the mass flow rate of the propellant is around 0.14066 kg/s. The thrusters weigh 1.9 kg each.

For the electrical propulsion, we choose the xenon propellant for the gridded-ion thrusters: NEXT thrusters systems [12] use electricity to accelerate the propellant to speeds of up to 40 km/s. Each weigh 8.2 kg and use 0.5 kW power. They can produce a force of 236 mN, and the specific impulse is about 4190 s.

6.5.2 Number of thrusters

The equation used in this part is presented below, connecting the force produced by n thrusters (F for one thruster), ejecting fuel at a mass rate $\Delta m/\Delta t$:

$$nF\Delta t = I_{sp} g\Delta m = v_e g\Delta m$$

We will find the number of thrusters by finding n for the worst case of our mission, meaning for the biggest maneuvers during the mission.

- For the chemical propulsion: we assume that our higher maneuvers consume a fuel mass of $M_{bp} = 2000kg$. Taking into account that the thruster can withstand a thrust for a maximum Δt of 6080 s (7600 s as tests shown, with 20% margin), we find that n = 4.9. Thus, we need 5 thrusters.
- For the electrical propulsion: the longest and biggest thrust is the spiral one when the S/C is quitting Earth gravity, consuming a xenon mass of $M_x = 195kg$, during a maximum time of 6560 hours (8200 h as tests shown, with 20% margin). We find n = 1.44, so we need two ion thrusters.

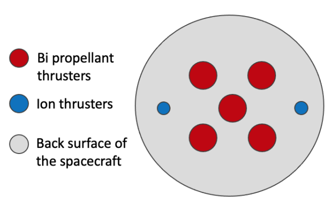

Fig. 11: Diagram of the thrusters placement at the back surface of the spacecraft

As we can see in figure 11, the bi propellant thrusters are centered on the S/C backface as they represent the main propulsion, and they are placed to allow a certain maneuverability. The 2 NEXT thrusers are placed on the exterior of the back face to have a better maneuverability, and have opposite position relatively from the center so that they can be used together for the first spiral phase but also non-simultaneously to make small adjustments during the maneuvers (also a reaction wheel allows rotation around the normal axis to increase maneuverability).

6.6 AOCS

The spacecraft shall be stabilized on the 3-axis in order to ensure a correct navigation during the mission. For that, as the mission [7], we will use a suite of:

- 3 Autonomous Star Trackers AA-STR by Leonardo, that have a field of view of 20x20 degrees. It enables the S/C to know its orientation.
- 3 FS Sun Sensors by MOOG, with a field of view of 128x128 degrees combined with an accuracy of 0.3 degrees. It's used for the orientation, based on the position of the sun.
- 1 IMU ATA by Aptec, which has a bias stability of 0.01 degree per hour. It's used to know the acceleration of rotation, and in all directions, of the S/C.
- 1 laser altimeter to determine the distance of the S/C to the surface of a planet/moon. In our case Jupiter for the gravity assist, Enceladus for the flybys and Saturn for a good elliptical orbit.
- 1 optical navigation camera (included in payload components), to perform close operations combined with star trackers.

Three actuators are used to maintain the S/C's orientation, starting with a set of four reaction wheels RW8 by Blue Canyon. They have a tetrahedral configuration, and provide a maximum torque of 0.11 Nm, with an angular momentum of 8 Nms. Also, the two NEXT ion thrusters are involved in the attitude and orbit control, and they will give a total Δv of around 1.5 km/s for the maneuvers (spiral thrust not included). Finally, we are also using an AOCS Control Unit by MOOG.

6.7 Thermal

6.7.1 General

The table of the temperature (in °C), using 2 different coats, is presented as followed:

Phase near:	Earth	Jupiter	Saturn
Goldenized kapton	282.7	-45.1	-103.6
Polished beryllium	446.9	39.8	-42.9

The outer body of the main S/C will be coated with Kapton 20 layer multi-layer insulation from Dupont, which have capabilities situated in between the goldenized kapton and polished beryllium. Also, we will manage the difference of temperature on the S/C by spinning, which can average the flux on all surfaces, thus not attaining the extreme temperatures. Radiators will also be required to keep the scientific equipment and other on board electronics at operational temperatures, as their work temperature range between usually -50°C and 70°C. Also, equipping the thermal control system with an electrical heater is essential. Finally, thermal isolators are used between the RTGs and propulsion part from the rest of the S/C.

6.8 Communications

The ELE mission's telecommunication system is taking advantage of the heritage from Cassini mission [6]. A Deep Space Transponder will provide a fully redundant dual X/Ka band telecommunication link. The S/C also features a 4-meter diameter HGA, that will provide scientific data transmission in X-band, and 2 backup LGAs operating in various frequency bands. When the S/C is not Earth-pointed, the LGA communication is provided as well as a X-band MGA (used during the commissioning phase and for emergency, providing telemetry data transmission). The ion thrusters are here to provide additional help for this matter. Concerning the modulation, it's a Quadrature Phase Shift Keying (QPSK), employed for the precise modulation of signals during up-link and down-link operations, allowing our S/C to convey data efficiently and reliably.

The Radio Frequency Subsystem (RFS) manages X-band up-link carrier tracking, telemetry modulation, and down-link carrier generation, supporting an up-link data rate of 160 bit/s. The Radio Frequency Instrument Subsystem (RFIS) efficiently handles Ka-band for essential radio-science experiments, providing down-link rate of 40 Kbit/s.

The ELE S/C establishes communication with Earth through the DSN, with facilities in Goldstone, Madrid, and Canberra. These locations are approximately 120 degrees apart, providing global coverage. The DSN employs antennas ranging from 34 to 70 meters in diameter, supporting X-band and Ka-band frequencies for carrier tracking, command up-links, telemetry down-links, and radio-science experiments. The DSN's continuous coverage ensures constant contact with Cassini, enabling the reception and decoding of telemetry and scientific information.

6.9 Structure and mechanisms

A trellis structure will be used for our S/C, and its overall form is a triangular prism. This type of structure, as seen in the picture (figure 12), has the advantage to homogeneously distribute the load, and gives multiple clips for the equipment. The S/C's structural materials will avoid excessive use of magnetic materials to maintain stability in attitude control and prevent interference with space physics measurements. The structure will mainly incorporate aluminum alloys, while also incorporating graphite–epoxy composite materials for both primary and secondary structures to leverage their superior mechanical properties.

To link the S/C to the launcher, we will use the launcher adapter interface F1663, that has a typical mass of 150 kg, so we have an available wet mass of 8120 kg (counting a margin of 20% from the launcher max capacity).

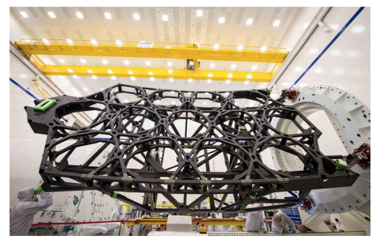

Fig. 12: Picture of an example of trellis structure

The S/C features 6 identical and independent sampling mechanisms: the standard sampling strategy, as [7], involves retrieving 5 samples and an additional 1 for onboard investigation. This redundancy is built for anomaly cases, and so that the scientists are sure to have information to analyze at the end of the mission. The sampling mechanism includes a spring, trigger, coil, C-shaped spring tape, and a canister with a shutter mechanism. After loading Enceladus's plume matter, the shutter secures the sample, and an electrically driven coil winds the canister back, keeping the sample at its original temperature. The manipulator arm then detaches and transfers the canister for analysis.

Other mechanisms are used as valves for the propulsion subsystem, a deployable antenna, and separation systems for the capsule samples to throw it on Earth and the payload to eject it on Saturn.

6.10 CDH

6.10.1 Data storage

As [7], the Onboard Computer is based on the LEON 32-bit RISC microprocessor. For one day, the duration of each Enceladus' flyby, the S/C accumulates approximately 1 Gb of data, following the summary of the data gathered by OWLS. For a complete mapping of the surface and other measurements with the radar during the flyby, a total amount of 1.5 Gb is required.

In the worst-case scenario, if the communication link with Earth fails, the system must have the capability to acquire and store all data until a new link can be established. We assume that the results can be transmitted at least once every orbit (so 1 over 3 communication phase). Therefore, taking into account other potential measurements during the elliptical orbit, redundancy and reasonable margin, a total data storage of 6 GB is preferable.

6.10.2 Data bus and protocols

A MIL-STD-1553 data bus [13] is used to connect all subsystems and instruments, including a single bus controller and up to thirty-one remote terminals. It's a serial bus which can support data-rates of up to 1 Mb/s. Science data is passed over the RS-422 interface at rates up to 900 kb/s, which is sufficient for our mission: during science mode the rate won't go over 600 kb/s with the scientific equipment on, and during communication mode over 300 kb/s.

For a message transmission from the bus controller to a remote terminal unit, the protocol involves a synchronization signal lasting for a 3 bits period, crucial for aligning the internal clock of the remote terminal with the bus controller. Following this, the address of the remote terminal is transmitted, accompanied by an RS/TX bit indicating the message direction. The message header includes a sub-address, message length, and a parity bit, followed by the transmission of the actual message when the controller initiates communication with the remote terminal. The reception acknowledgment includes the receiver's address and a status word indicating the reception outcome.

For receiving a message, the remote terminal first responds with its address and status word, followed by the message.

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