SEAFARER
Alpbach Summer School 2024
Team Green

July 17, 2024

Science Team: J. Bürger, E. Juul, C. Ntinos, B. Quanten, D. Quirino, F. Weichbold, J. Wiltenburg
Engineering Team: V. Affatato, A. Baranyai, B. Baudel, A. Bouis, C. Daly, A. Ohm, D. Placke, E. Sango, S. Vaghi

Abstract: The **S**urveying **E**nvironments **A**cross the **S**aturnian **S**ystem **F**or h**A**bitability **R**es**E**a**R**ch (SEAFARER) is the mission concept proposed to address the scientific questions arising from the results of the Cassini-Huygens mission. The main focus is studying and characterising the diversity of habitats in the Saturnian system. The habitability potential of the icy moons of Saturn was first discovered by the Cassini-Huygens mission, but it was not designed nor suitable to investigate this topic in depth. To fully address the habitability potential of key bodies in the Saturnian system, an ambitious and compelling three segment mission is proposed. 1) The VESPUCCI (**V**ertical **E**ntry probe for **S**aturn's **U**pper **C**loud **C**hemistry and habitability **I**nvestigation), will measure the composition and physical properties of the Saturnian atmosphere. 2) the COLOMBUS (**C**hemical and **O**rganic **L**ander for **U**nderstanding **M**ethane-**B**ased **U**nderwater **E**nvironment**S**) will measure liquid composition and study the meteorology of Titans atmopshere and liquid body characteristics, by deploying directly into the Kraken Mare. 3) COOK (**C**ollaborative **O**rbiter for **O**bserving **K**ronos) will map the surfaces of the icy moons namely Enceladus and Mimas using remote sensing during a number of flybys. COOK carries dedicated instrumentation to study the plumes of Enceladus, as well as the Saturnian rings. Additionally, medium sized moon will be studied during opportunistic flybys. COOK will end its journey in an orbit around Titan where it will assist COLOMBUS with remote sensing of Titans atmosphere. This mission will significantly advance the understanding of the habitability potential of the natural laboratories present in the Saturnian system.

1 Introduction

The outer planets in the Solar System offer exciting opportunities to explore planetary and moon diversity. Gas giants have been less studied than the inner terrestrial planets due to several engineering challenges, such as operating a spacecraft (S/C) and its systems in a low-energy environment. Nonetheless, the scientific returns of exploring these planets and moons can potentially transform present-day planetary science. Additionally, the giant planets and their moons serve as archetypes for understanding the diversity of worlds in the cosmos.

The Saturnian system, in particular, encompasses a diversity of environments and potential habitats within the same system of moons, like ocean worlds (e.g. Enceladus) and a cold prebiotic world on Titan. These worlds are natural laboratories for complex physical and chemical processes and, therefore, suitable for addressing a broad spectrum of research questions relating to habitability. Starting with Saturn, unravelling its atmosphere composition and isotopic ratio abundances will allow us to constrain where the planet formed and how its orbital parameters evolved. This has far-reaching implications for the nature of present-day solar system architecture and possibly water delivery to the inner terrestrial planets [1].

On Enceladus, it is suspected that tidal heating is responsible for a global subsurface ocean with hydrothermal activity in its seafloor, as shown by the detection of silica particles in Saturn's E-ring [2–5]. The Cassini-Huygens mission detected plumes of water vapour, other volatile materials (e.g. molecular hydrogen) and particulate materials (e.g. water ice and salts) over the moon's geologically young south polar region [6–8]. These plumes allow the indirect characterisation of the internal ocean and the nature of its water-rock interactions [7]. Moreover, detecting complex organic compounds through plume sampling would be a significant scientific discovery, updating the current habitability status of this world [9].

Another moon in the Saturnian system that the mission will visit is Mimas, where recent modelling efforts suggest the existence of a young (~ 25 Myr), still-evolving, subsurface ocean [10]. To confirm the presence of the internal ocean of Mimas, new measurements are required, e.g. detecting aqueous mineral alteration [11]. Furthermore, quantifying the longevity of a subsurface ocean is crucial to assessing the habitability potential of ocean worlds in general and internal heating via the evolution of orbital parameters [12].

Titan is the second-largest moon in the Solar System and the only moon which has a significant atmosphere, dominated by nitrogen (N_2) and methane (CH_4) with a surface pressure of ~ 1.5 bar [13]. Cassini discovered the seas, lakes and rivers in the moon's northern polar region [14]. Apart from Earth, Titan is the only other body that possesses climate variability on timescales that are conceptually similar to the ones found on Earth [15]. Underneath an icy crust containing hydrocarbons and water ice, a subsurface water ocean is possibly mixed with ammonia, preventing its freezing [16]. Understanding how these two layers interact and transport organic matter or water solutions through the icy surface is of paramount importance within the framework of habitability [17]. Moreover, Titan orbits mostly inside Saturn's magnetosphere, presenting a unique case to explore the interactions between the magnetosphere and upper atmosphere (ionosphere), which can be relevant for the long-term mass budget of such an atmosphere [18]. For all these reasons, Titan remains the best natural laboratory to study climate and its change outside the Earth from both a palaeoclimate and exoplanetary perspective. The present understanding says that Titan's atmosphere is under a greenhouse effect caused by methane [19]. Interestingly, precipitation occurs predominantly in the summer months in the polar regions [13–15]. However, a 3D interpretation of the large-scale circulation features (such as the super-rotation and polar vortex) is missing, together with a full-scale perspective of the CH_4 cycle [15, 17]. In particular, understanding complex haze formation in Titan's upper atmosphere can help improve 3D global circulation models of the atmosphere, which are used to interpret exoplanet observations [20].

Based on the previous heritage and major research avenues, we present the mission concept Surveying Environments Across the Saturnian System For hAbitability ReSEaRch (SEAFARER), designed to address planetary habitability's most pressing scientific questions. The European Space Agency's (ESA) commitment to further exploration of the Solar System's giant planets and their moons is confirmed by the Voyage 2050 mission: a long-term science programme consisting of multiple large class-science missions. The SEAFARER mission falls within the area of interest of Voyage 2050 for an L4 mission. We propose to select the Saturnian system for this study because the concentration of diverse habitats in the same system offers a unique opportunity to maximise the scientific return, improving humankind's understanding of planetary habitability.

2 Mission goals

The mission aims to study and characterise the habitability of the Saturnian system. This specific system was chosen because of the variability of its potentially habitable environments. The SEAFARER mission will give valuable insight into the formation of the system, the influence a planet has on its moons, and to which extent biotic and complex chemical molecules can form under the predominating environmental conditions. This will add to the knowledge about exoplanets' formation and habitability possibilities.

2.1 Science Objectives

To meet the mission goals, the following science objectives were designed:

1. **SO1**: How and where did Saturn form?

2. **SO2**: What is the nature and diversity of the potential habitats?

3. **SO3**: What is the peculiar nature of the Titan climate variability?

2.2 Science Questions

Based on the aforementioned science objectives, the critical science questions are highlighted in Table 1.

Table 1: Critical science questions

Q1.1: What is Saturn's formation history, composition and implications for the present-day solar system architecture?
Q1.2: What are the physical, dynamical and radiative conditions of the upper atmosphere of Saturn in the pressure range between <1 bar and 10 bar?
Q2.2: What is the geomorphology and composition of Enceladus' surface in the moon's south polar region?
Q2.3: What is Enceladus' plume activity variability (location, composition, time, interaction with magnetosphere)?
Q2.5: What is the nature of the potential subsurface ocean on Mimas?
Q2.7: What is the current state of interior-surface processes on Titan, their global distribution, geological history and implications for organic material transport across the icy crust?
Q2.9: Are biogenic elements present in the organic chemistry in Titan, and, if so, what are their abundances?
Q3.1: How do the large-scale atmospheric features on Titan (superrotation, polar vortex) evolve?
Q3.2: What is the meteorology (temperature, surface winds, pressure, methane humidity precipitation, heat flux) in the northern polar region of Titan?
Q3.6: What is the complete distribution, physical and dynamic properties of lakes and river networks on Titan and their temporal variability across different latitudes?
Q3.8: What are the local physical and dynamical properties of Kraken Mare as a proxy for Titan's lakes and seas?

To answer these scientific questions, in-situ measurements shall be performed, as well as high-resolution remote sensing.

2.3 Instruments and their driving measurement requirements

To answer the posed science questions, a list of instruments with the most important requirements has been identified and is presented in Table 2.

2.4 Preventing extra-terrestrial contamination

This mission to the Saturnian system is a COSPAR policy on planetary protection category II, where "*Category II missions comprise all types of missions to those target bodies where there is significant interest relative to the process of chemical evolution and the origin of life, but where there is only a remote1 chance that contamination carried by spacecraft could compromise future investigations*" [21].

Table 2: List of instruments and driving requirements

Orbiter (COOK)
Visible & Infrared spectrometer (VIRS) shall have a spectral range 0.5 μm to 5.5 μm, with spectral resolution of $\sim$ 10 nm and a spatial resolution of down to 0.075 km/pixel.
Sub-millimeter wave instrument (SWI) shall have two spectral ranges 1080 GHz to 1275 GHz and 530 GHz to 601 GHz with spectral resolving power of 1×10^7. Updated to include a third channel: 300 – 360 GHz.
Camera: optical and near-IR system. Shall have three channels at 1.3 μm, 2 μm and 5 μm.
Mass spectrometer (MS) shall have a Mass range $\geq$ 1000 amu and a mass resolution of $> 100M/\Delta M$.
Magnetometer (MAG) shall have a time resolution of 30 Hz and an accuracy of 100 pT.
Ultraviolet Spectrometer (UVS) shall have 50 nm to 204 nm bandpass with 0.4 nm spectral resolution and a spatial resolution of $\leq 0.3\,^{\circ}$.
Radar (RAD) shall have a resolution of 0.35 km to 1.7 km.
Gravity Science Experiment (3GM), a radio package comprising a Ka transponder, an ultrastable oscillator and a high-accuracy accelerometer.
Dust Analyzer (DA) shall have a measurable particle mass range interval of 10^{-16} kg to 10^{-10} kg

Probe (VESPUCCI)
Mass spectrometer (MS) shall have a mass range of 2 amu to 150 amu with a mass resolution of $M/\Delta M = 120$ at 75 amu
Tunable Laser spectrometer (TLS) shall have a resolution of 1×10^5 $\lambda/\Delta\lambda$
Lightning and Radio Emissions Detector (LRED) shall have a frequency range of 0.1 kHz to 100 kHz
Acclerometer (ACC) shall have a accuracy of 0.1 m/s^2
Nephelometer (NEM) shall have a resolution of 0.1 μm
Net Flux Radiometer (NFR) shall have a resolution of 1 km
Pressure Sensor (V-PS) shall have an accuracy of 1 Pa
Temperature Sensor (V-TS) shall have an accuracy of 0.1 K

Lander (COLUMBUS)
Gas Chromatograph-Mass Spectrometer (GC-MS) shall have a mass range from 2 amu to 500 amu and a mass resolution shall be 1×10^{-6} at 250 amu
Sonar shall have a frequency of 20 kHz with vertical precision of 0.1 m
Dielectric constant sensor (DCS) shall have a resolution of 1×10^{-12}
Temperature sensor (C-TS) shall have an accuracy of 0.1 K
Pressure Sensor (C-PS) shall have an accuracy of 1 Pa
Camera shall have a resolution of 2 m/pixel with two channels at 2.4 nm and 6.3 nm
Nephelometer (C-NEM) shall have a resolution of 0.1 μm

3 Mission Architecture

3.1 Mission Timeline and analysis

Considering previous L-class missions developed by ESA, the mission development phase is expected to take $\sim$ 15 years. Coherently, the timeline presented in Table 3 refers to a launch opportunity for the mission on 1/11/2043, providing a $V_\infty = 3$ km/s with respect to Earth's velocity; similar transfers can be achieved every 12.5 months. According to studies for Saturn missions, the launch window would be open for 21 days, with a limited (max. 1 km/s) to no variation of insertion velocity V_∞. The identified cruise to reach the Saturnian system is based on an 'EEES' trajectory studied at the ESA Concurrent Design Facility [22] and it is reported in Figure 1, including two flybys of the Earth and three Solar Electric Propulsion (SEP) arcs in between. The second one is the farthest from the Sun, at a distance of 2.2 AU, and constrains the total power required from the solar array to 7.5 kW. Solar panels have been sized accordingly.

Table 3: SEAFARER mission timeline, based on similar proposals [23]. **EGA**: Earth Gravity Assist; **SOI**: Saturn Orbit Insertion; **PRM**: Periapsis Raising Manoeuvre; **EOL**: End-of-Life.

Phase	**Date(s)**
Launch	1/11/43
EGAs	4/4/45 & 17/4/47
SOI	1/8/52
PRM 1	24/10/52
Mimas flybys	31/12/52 - 31/8/54
PRM 2 and Titan flybys	30/11/54 - 20/3/55
Enceladus flybys	20/3/55 - 26/6/55
Titan orbit & EOL	13/1/56 - 13/1/57

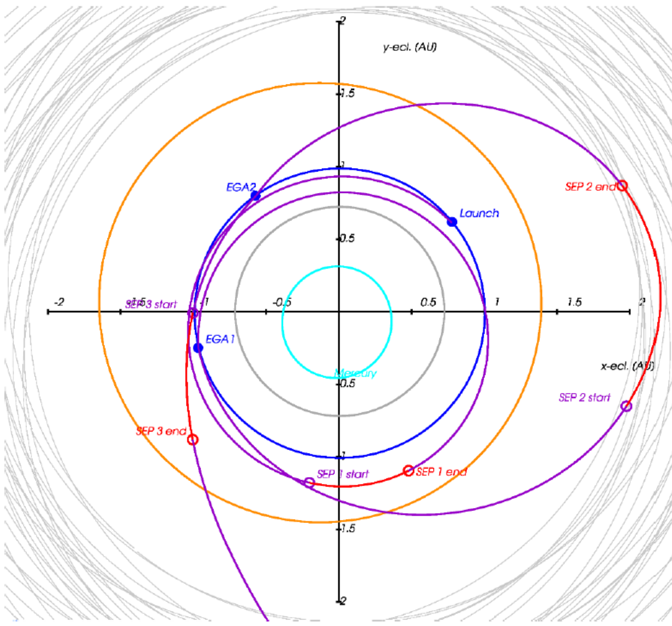

Figure 1: Interplanetary transfer to Saturn. The proposed EEES approach involves two EGAs and three SEP ARCs.

After the last SEP arc, the SEP module, including the solar panels, can be jettisoned to remove some inert mass. Indeed, power generation in the Saturnian system will use Radioisotope Thermoelectric Generators (RTGs). The propulsion system inside the Saturnian system is based on chemical propulsion. The next phase involves the approach to Saturn, which will happen with a $V_\infty = 5.56\,\mathrm{km/s}$. The S/C's entry trajectory is inclined by 55° w.r.t. the Saturnian equatorial plane. The proposed cruise presents a perikrone altitude of 2000 km above the 1-bar level of the Saturnian atmosphere. Concerns may arise about the risks associated with such a close passage. However, Cassini performed a similar manoeuvre during its *grand finale*, demonstrating that atmospheric drag will not cause any damage to the S/C. An additional criticality is the VESPUCCI probe release: a sufficient communication window shall be guaranteed before the probe disintegrates in the atmosphere. At the same time, the perikrone passage is a key phase for the mission, and communication with Earth is usually necessary. For this reason, the VESPUCCI probe will be released on a colliding trajectory with Saturn's surface a few months before reaching the perikrone. During release, the S/C's trajectory perikrone can be increased to slow the S/C and ensure the maximum coverage possible for the probe. Another option to make the release safer is to release the probe only after the SOI has been performed; however, this solution would lead to a larger propellant mass required for the SOI itself since the probe mass should still be included.

The moons' tour is performed with the following sequence: the first orbit around Saturn, which takes slightly more than four months, is used to perform the PRM at the 10-million km apokrone and raise the perikrone to Mimas radius. A minimum amount of five Mimas' flybys are foreseen to accomplish the scientific objectives. Each approach requires a four-month orbit. A second PRM manoeuvre is needed to raise the perikrone to 300 000 km. From this orbit, 8 swingbys of Titan can be performed, aiming at inserting the S/C in a 7:1 resonant orbit with Enceladus with minimum propellant consumption. A series of 10 flybys of Enceladus, with a total duration of 96 days, is performed at this stage. The entire tour is also exploited to decrease the inclination of the orbit from the initial 55° to 20°, with which COOK will approach its final destination: Titan.

Table 4: Moons tour flybys specifics. A 120° window for the scientific measurements has been considered for each flyby.

Flyby	N°	Min. altitude [km]	120° Scientific Window Duration [h]	Total Duration
Mimas	5	50	12	20 m.
Titan	8	1200	130	70 d
Encelad.	10	50	7.2	96 d

The last phase of the mission starts with a similar approach to the one used for the VESPUCCI release in Saturn. The S/C is inserted into an entry trajectory to Titan, on which, three days before the TOI (Titan Orbit Insertion), the COLUMBUS lander will be released. The landing site identified by the scientific case is the Kraken Mare (70°N, 50°E), one of the big lakes found by Cassini between 70° and 78° N on the moon. The final choice was driven by the dimension of the lake and the possibility of inserting the S/C into a lower inclination orbit to avoid excessive perturbation by Saturn. The orbiter will be inserted in a 2500 km altitude circular orbit around Titan. From this orbit, the orbiter can guarantee enough coverage and act as a relay for the ten days of operative life of the lander. However, an interesting alternative consists of inserting the orbiter in a 35 000 km altitude HALO orbit around the L1 Lagrangian point of the Saturn-Titan system, which guarantees full coverage. After the operational life of the lander is over, close manifold transfers to the L2 point can be exploited to guarantee scientific observations closer to Titan's surface [24]. Moving the orbiter from the manifold to the previously presented circular orbit is also possible, with a total ΔV comparable with the nominal one (0.6 km/s). The orbiter's nominal operational lifetime around Titan is one year. The margins included for the propellant mass budget are expected to provide an extension of at least a year, with the possibility of changing the orbital parameters to observe other surface regions. In either case, the S/C can be disposed of by exploiting the perturbations induced by Saturn without further manoeuvres. The orbiter will enter the atmosphere during disposal, allowing for some additional end-of-life scientific measurements. This solution for the disposal on Titan is considered safe according to the COSPAR planetary protection policy [21].

3.2 Launcher Selection and ΔV budget

The ΔV budget for the proposed mission plan has been investigated. Using a Xenon-based electric propulsion system for the interplanetary cruise with a specific impulse (I_{sp}) of 4400 s and an MMH-N_2O_4 bi-propellant liquid system for the moons tour with a I_{sp} of 320 s, the estimation on the required ΔV is presented in Table 5. According to the ESA margin policy, a ΔV of 35 m/s and 15 m/s have been accounted for gravity assists around planets and minor bodies, respectively. A 5 % margin is also added to deterministic manoeuvres. Eventually, a 10 % increase in the final propellant mass is included to account for unforeseen events and a possible mission extension for lower altitude orbit around Titan. After an iteration on the required wet mass of the S/C, the estimated mass at launch is 7.5 tons. Despite the advancement provided by Ariane 6, the current launcher can not guarantee such high launch mass. Nevertheless, in order to prioritise the use of a launcher developed from an European consortium, a future

Table 5: ΔV budget for the mission and total propellant mass identified. The former includes a 5% margin for the manoeuvres, while the latter a 10% for unforeseen manoeuvers and possible mission extension.

Mission Phase	ΔV [km/s]	Propellant Mass [kg]
Interpl. Cruise	3,11	572
Saturn Approach	0,72	1218
Moons Tour	0,45	744
Titan Orbit	0,81	1084
AOCS allocation	0,10	218
TOTAL	5,10	3838

version of the Ariane 6, the Ariane 64 EVO, is considered for this mission. Although no official data has yet been released, the latest predictions foresee a significant payload increase for Earth escape orbits to roughly 9.5 tons, considering a V_∞ of 3 km/s. The geometrical specifications of the Ariane 64 fairing will remain unchanged at a maximum diameter of 4.7 m and a maximum height of 18 m. Therefore, a launch mass of 7.5 tons can be considered acceptable.

3.3 Mass and Power Budgets

The mass budget is broken down in Table 6 with ESA ECSS mass margins of 5 %, 10 %, and 20 % added depending on each design's maturity and heritage. A 30 % system margin has been added to account for the early stage of the mission and its classification as an interplanetary mission study. The dry mass is given in three critical moments: after the final SEP manoeuvre (2850 kg), after the launch of the probe (2520 kg), and finally, after the launch of the lander (2221 kg).

Table 6: Mass budget

Subsystem	Total Mass (kg)	Percentage Dry Mass (%)
Communication	215	7.9
SC Instruments	297	10.8
Titan lander	299	10.9
Saturn probe	270	9.8
AOCS	96	3.5
Power	215	7.9
Thermal	63	2.3
SEP	393	14.4
Chemical prop.	210	7.7
Structure	679	24.8
Dry Mass Total	2740	100
System Level Margin	822	30
Harness Margin	137	5
Dry Mass with System Margins	3698	NA
Xenon Propellant	573	NA
Mono Propellant	3265	NA
Total mass of S/C at lift-off	7538	NA

The power budget is visualised in Table 7, where the power of the subsystems is given during the driving mission modes. Again margins of 5 %, 10 %, 20 % were added based on the maturity of the technology.

Table 7: Orbiter: Power budget

Subsystem Driving Modes	Science (W)	Earth Comms (W)	Science Comms (W)
Communication	-	290	268
SC Instruments	371	-	-
AOCS	82	63	63
Power	18	18	-
Total Power	454	372	350

4 Ground Stations

Key to all space missions is the need to send telemetry and science data back to Earth. To do so, the mission will require using ESA's Deep Space Network (DSN), which has 35 m dishes at Cebreros, New Norcia, and Malargue. The ground stations will communicate with the orbiter to download the measured scientific data and telemetry. The Ground station will also send commands to the orbiter if preprogrammed values must be changed or automation cannot be used. The orbiter will communicate with the DSN through Ka-band (26.5 GHz to 50 GHz) using a 4 m stiff gimbaled High Gain Antenna. During commissioning and safe modes, the X-band (8 GHz to 12 GHz) will be used. Considering the distance between Saturn and the Earth, the lander and the probe will not directly communicate with Earth. Instead, their telemetry and science data will be relayed by the orbiter using X-band and Ultra-High Frequency (UHF; 0.3 GHz to 1 GHz), respectively.

The Saturnian system is 10.5 AU away from Earth in the worst-case scenario. As such, communications are limited by engineering constraints rather than science requirements at this stage. Accounting for windows of contact ranging between 5 h/day (as expected by the Enceladus Orbiter mission) and 8 h/day (like JUICE), the maximum data downlink is 720 MB/day at the worst and 1.15 GB/day transmitted at a rate of 40,000 bps.

The windows of communication constrain the link between the orbiter and the lander. With an orbital period around Titan of 6.25 hr and an X-band's horn antenna's beamwidth of 12°, only 13 min of communications can be confirmed. The additional time provided by the AOCS pointing the orbiter towards the lander is counteracted by the need for the orbiter to first find the lander before establish communications (see section 7 regarding the lander). The expected high absorptivity of Titan must also be considered for the link budget. With this in mind, a maximum data rate of 40,000 bps allows for a maximum data transmission of 32 MB/day.

5 Orbiter COOK

The purpose of the SEAFARER mission is to characterise the habitability of the Saturnian system, specifically to assess the formation of Saturn, investigate the nature and diversity of the potential habitats, and examine Titan's climate. The orbiter segment's purpose is to perform remote sensing of Saturn and its moons, Enceladus, Mimas, and Titan, as well as any opportune flybys of Saturn's medium-sized moons. The orbiter will also act as a communications relay between the probe and lander and back to Earth.

During the cruise phase of the mission, the "COOK" lander will carry the "VESPUCCI" probe and the "COLUMBUS" lander. The orbiter will transport the probe and the lander to their respective destinations, highlighting the complexity of the configuration designed for extensive exploration of the Saturnian system.

One of the identified risks of the mission are the deployment mechanisms for some of the instruments. Articulated structures include the ones for the High Gain Antenna (HGA) and the solar arrays. Deployed structures include the ones for the solar arrays, magnetometer boom, radar antenna, lander and probe deployment mechanism. In addition to sensor data, cameras on the orbiter will be used to confirm the deployment of each respective module.

The preliminary design of the COOK orbiter and its key features are shown in Figures 2, 3, 4.

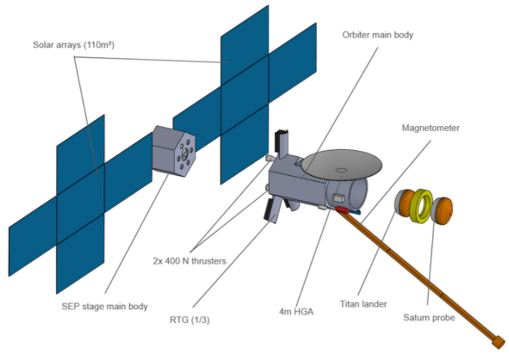

Figure 2: Orbiter design

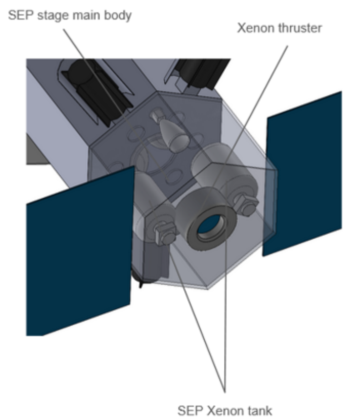

Figure 3: First stage design

5.1 Propulsion System

As discussed in Section 3, electric propulsion will be used for the interplanetary cruise, whereas a chemical propulsion system will be used in the Sarturnian system. The key features of both systems are summarized below:

- SEP propulsion: Xenon propellant, $I_{sp} = 4400$ s, capable of providing 54 mn/kW thrust.
- Chemical propulsion: MMH+NTO bi-propellant, $I_{sp} = 321$ s provides the necessary thrust for the S/C to reach Saturn and its moons.

5.2 Payload / Instruments

The following scientific instruments will be on the orbiter to fulfil the mission requirements: UV-spectrometer, Infrared spectrometer, Mass spectrometer, Camera, Magnetometer, Radar, sub-mm wave instrument, and Dust Analyser. Appertaining (pre)process and compressing hardware is also

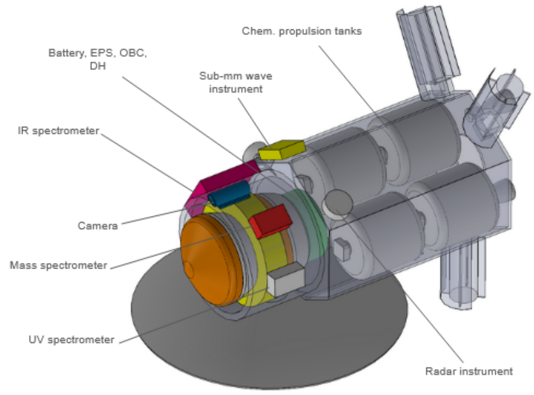

Figure 4: Second stage design

mounted. Using these devices, measurements can be conducted to form answers to the science questions of SO2 and SO3, shown in Table 1.

5.3 Power

The orbiter's expected maximum power consumption happens during the SEP phase and consumes 7488 W, which are provided by the solar electric propulsion arcs. However, once the Saturnian system is reached, the power consumption drops to a maximum of 600 W when operating in Science mode (see Table 7).

At the beginning of the mission, the 110 m^2 solar arrays generate around 7.5 kW of electrial power at 2.2 AU (where the final SEP manoeuvre will take place). The selected solar arrays are two JUICE-like panels made of Gallium Arsenide (Ga-As). These cells provide electricity during the cruise until the separation phase is reached. Since the solar irradiance reduces with the inverse square of the radius from the sun, the SEP stage, containing the Xenon thruster, tanks and solar arrays, is jettisoned at roughly 2.2 AU and sent into a collision orbit with Saturn. This ensures the disposal of the arrays so as not to endanger any future missions to this region.

Once the solar arrays have been jettisoned, the orbiter uses three General-Purpose Heat Source (GPHS) - RTGs (similar to New Horizon, Cassini) to power the main instruments of the Orbiter for the remaining mission duration. Despite their low efficiency, RTGs were selected compared to larger solar panels or nuclear power. However, a disadvantage of RTGs is their high thermal heat output, which creates restrictions in the design of the spacecraft. It also brings requirements such as that sensitive systems must be adequately protected from the produced heat and radiation. Batteries will be included which will be charged by the RTGs to provide power to the spacecraft.

5.4 Thermal Control

The thermal control system is designed to maintain all instruments and mission components within their ideal operational temperature ranges. This subsystems key drivers are the temperature requirements set by the propellants, batteries, onboard computers, and scientific instruments. Although most instruments mainly operate within comparatively warmer ranges of 240 K to 310 K, some instruments like the IR spectrometer require passive cooling to operate at low cryogenic temperatures.

As mentioned, the RTGs produce high amounts of excess heat (∼ 4400 W per RTG). To avoid overheating, the design of the orbiter was inspired by Cassini's implementation of RTGs, which were placed at the bottom of the S/C to keep them isolated and far away from the rest of the instruments at the top of the S/C. This configuration also allows for the RTGs' heat to be radiated away into deep space.

The orbiters thermal system consists of several layers of Multi Layer Insulation (MLI) blankets, which will prevent heat loss from critical components and excessive heating, especially from the RTGs. To vent the heat from the system, louvres will be used to change the orbiter's average IR emission and manage how much heat the surface dissipates. A passive heat dissipation system dissipates the heat generated by the RTGs. It consists of an aluminium alloy case with four fins and an 8 cm layer of Astroquartz III® insulation.

5.4.1 AOCS

The communication instruments on board the orbiter require precise pointing, and scientific instrumentation requires high pointing stability. As such, a 3-axis stabilisation scheme was selected despite its increased complexity and cost compared to other methods, such as spin stabilisation.

On board the orbiter, attitude control is performed by AOCS controllers based on information provided by the Inertial Measurement Units (IMUs) and supported by data from sun sensors and star trackers. During safe mode operations, only the sun sensors will be used to maintain a point in the direction of the Earth while waiting for communications.

Attitude control is maintained using a set of four 25 Nm*s reaction wheels. These wheels will store the moment accumulated due to disturbances from gravity-gradient, atmospheric drag (both around Saturn and Titan's dense atmosphere) and Saturn's magnetic field torque, as well as due to maneuvers performed by the orbiter. The wheels will require to be desaturated periodically. During that time, the orbiter's pointing will be ensured by N_2 cold gas thrusters, the same ones used during manoeuvres. To account for the still uncertain magnitude of the orbit and pointing disturbances throughout the mission, a delta-V budget of 100 m/s was considered.

6 Probe VESPUCCI

The SEAFARER mission includes a probe to investigate Saturn's atmosphere. The probe has a mass of 300 kg and is designed to have a peak power of 140 W and a diameter of 1.3 m. Its parachute's diameter is 2.5 m, which should manage the temperature up to 14 000 K due to protection by a special heat shield. For this, Galileo's probe concept has been used.

The probe's design has for heritage the Galileo probe which entered the Jovian atmosphere. It also takes inspiration from the Planetary Entry Probes CDF studies which investigated re-entry of probes into various atmospheres, including Saturn's. VESPUCCI's goal is to determine Saturn's formation history, its composition, and the dynamics of its atmospheric

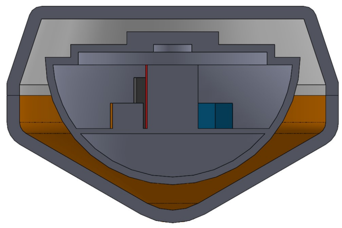

Figure 5: Probe design

environment. As such, much like was envisioned from the SPRITE mission, VESPUCCI is designed to reach a minimum of 10 bars and maintain contact with the overhead orbiter during entry. The specifics of its entry timeline are shown in Figure 6.

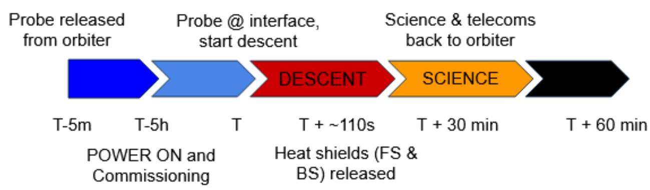

Figure 6: VESPUCCI probe mission development

The probe will be released from the orbiter 5 months before it arrive in orbit around Saturn. To conserve its limited power, VESPUCCI will remain in hibernation until 5 h before its entry in the atmosphere; at which point it will power on and perform its commissioning. Once it reaches the interface with the atmosphere, the probe will start broadcasting its data back to the orbiter. To slow its entry and enable the probe to survive past the depth of 200 km (at which the pressure is of 10 bar), 2 parachutes will be used. The main parachute has a size of 8.3 m (diameter) to help the scientific mission due to short data measurement period (at least 1 hour) before probe will burn up.

To meet the probe's maximum simultaneous power of 140 W (as set by the instruments, subsystems, and their margins), a rack of 4 $LiSO_2$ primary batteries 3 kg is used. No RTGs are needed due to the expected short measurement period of approximately 60 minutes.

A key driver of the probe's design is the need for it to survive the re-entry into the Saturnian atmosphere. Specifically, it shall survive the high temperatures resulting from this entry, even when mitigated using a parachute. To manage the expected heat of ∼ 14 000 K, the probe will include a front and back shield weighing ∼ 120 kg. Probe instruments will be further shielded using MLI and thermal insulators. The instrumental payload will need to be stabilized by the temperature control system to temperatures between 253 and 318 K, or performance degradation will be observed.

The communication subsystem manages the telemetry data and data collected by scientific instruments. The collected data is transferred to the orbit. To do so, the probe will have a patch antenna on its back shield and a helical antenna on the probe itself. A UHF frequency was selected for the uplink as it was the least absorbed by the Saturnian atmosphere, and whith therefore a longer transmission time.

As in the case of the orbiter, telemetry data and data generated by scientific instruments will be collected and transferred by the communication system using the Antenna on the probe. To do that, measured and (pre)processed data will be sent to the orbiter. The following instruments are onboard: Thermometer, Pressure, Net Flux Radiometer, Nephelometer, Axial, Accelerometer, Lateral Accelerometer, Lightning and Radio Emissions Detector, Mass spectrometer and a Tunable Laser spectrometer. More details in section 2.3.

7 Lander COLUMBUS

As part of the SEAFARER mission, a detailed investigation of Titan and its climate will be performed. This is accomplished through remote sensing by the orbiter and through the landing of COLUMBUS on one of Titan's liquid methane lakes, Kraken Mare. Following in the footsteps of the Huygens probe, COLUMBUS will perform a soft landing on the liquid lake and operate for approximately 10 days. It will perform scientific analysis of its nature and climate. The details of the lander segment timeline are shown in the following Figure 7:

COLUMBUS will follow and perform a similar descent as the Huygens probe with drogues and parachutes. The main parachute size is 8.3 m (diameter) to help achieve a soft landing on the Kraken Mare. The lander will be protected with a heat shield during its descent. It will enter at a speed of 4.0 km/s from an altitude of 1270 km, with both inertial and relative entry angles close to -45°. Its design incorporates a 60° sphere-cone shape with a nose radius of 1.25 meters and a base area of 5.73 m^2. During peak heating, it will experience a velocity of about 5.1 km/s and convective heating of 29.3 W/cm^2, while radioactive heating is negligible at approximately 0.1 W/cm^2. The total heat load integrated over the mission is about 1397 J/cm^2. Three parachutes made from nylon with Kevlar structural supports assist in the landing, deploying through a mortar for the pilot and main parachutes under specific dynamic pressures and Mach numbers [23].

To ensure that COLUMBUS will land on liquid, an assessment of the ellipse of confidence for the lander's drop location was performed using the following equations:

$$m\frac{d^2x}{dt^2} = mg\cos(\theta) - D\left(\frac{dx}{dt}\right)^2, \tag{1}$$

$$m\frac{d^2y}{dt^2} = -mg\sin(\theta) + D\left(\frac{dy}{dt}\right)^2, \tag{2}$$

$$D = \frac{1}{2}\rho v^2 C_d A,$$

In this case, the atmospheric density changes are not considered. This solution is an approximation of the trajectory for entering the atmosphere.

$$v_x(t) = \sqrt{g\cos(\theta)}k\tanh\left(\sqrt{g\cos(\theta)}kt + \tanh^{-1}\left(\frac{kv_x(0)}{g\cos(\theta)}\right)\right)$$

$$v_y(t) = \sqrt{g\sin(\theta)}k\tanh\left(\sqrt{-g\sin(\theta)}kt + \tanh^{-1}\left(\frac{kv_y(0)}{g\sin(\theta)}\right)\right)$$

$$k = \frac{\rho C_d A}{2m}$$

The location of the landing is shown in Figure 8 .

COLUMBUS' geometry has been designed to enable it to float on the liquid methane lake and perform scientific investigations of the liquid below. The buoy consists of a cylindrical (upper buoy) and a conical part (lower buoy). The lander's cylindrical shape is designed to minimize the stresses caused by the pressure and thermal conditions of Titan. The average temperature on Titan's surface is -180ºC.

$$\sigma_{Tr} = \frac{p_i R_i^2}{R_e^2 - R_i^2}\frac{2R_e^2}{R_i^2}$$

$$\sigma_{Tr} = \frac{2\mu\alpha(3\lambda + 2\mu)}{\lambda + 2\mu}|\Delta T|$$

Once landed on Kraken Mare, the lander separates into two parts: upper and lower buoys. The upper segment will host the batteries, heaters, X-band communication transceivers, and atmospheric instruments; while the lower segment will host the Gas-Chromatograph Mass Spectrometer (GCMS), sonar, and sensors needed to obtain Titan's lake's temperature, pressure, and density vertical profile. However, due to the mechanical limitations of the hoist mechanism, a maximum depth of five meters seems reasonable. The mechanism consists of the lower buoy lowered by cables, a gear system, and a retraction mechanism. Cryogenic temperatures affect the compliance of the cable material.

The lander thermal protection system includes an AQ60/I material heat shield, with a thickness of 17.4 mm at the stagnation point and 18.2 mm on the flanks. The thermal protection system weighs 39 kg, with the structural components adding another 76 kg. They are designed to ablate and eject material under high heat conditions. The aft body is made from Prosial®, varying in thickness from 0.03 to 0.31 cm, and contributes an additional 5.2 kg for thermal protection and 17 kilograms for the structure. At the surface, the heaters would provide 20-50 W of heat to maintain internal temperature at 10-20 degrees. The isolation is done using 20 cm of multi-layer isolation resin.

Communication between the COLUMBUS and COOK will be ensured via X-band communications. First with a patch antenna on the backshield so as to monitor the re-entry process, and then with a helical antenna on the lander. The helical antenna is needed as COLUMBUS is a "drifter", not having any power to propel itself. As such, the wind and possible tidal currents are expected to push this buoyant craft around the sea, requiring for the antenna onboard to be omnidirectional to enable a quick contact acquisition with the overhead orbiter.

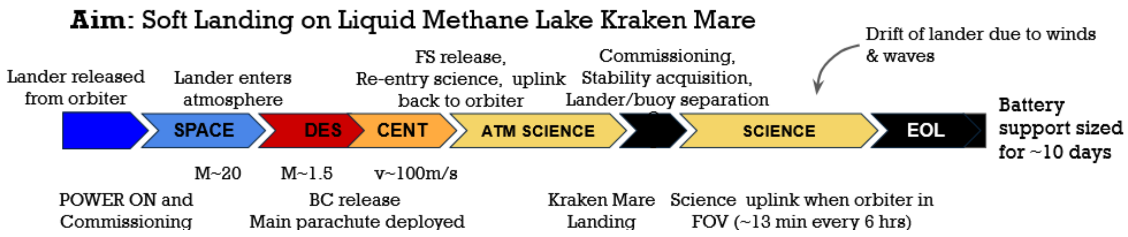

Figure 7: COLUMBUS lander mission plan

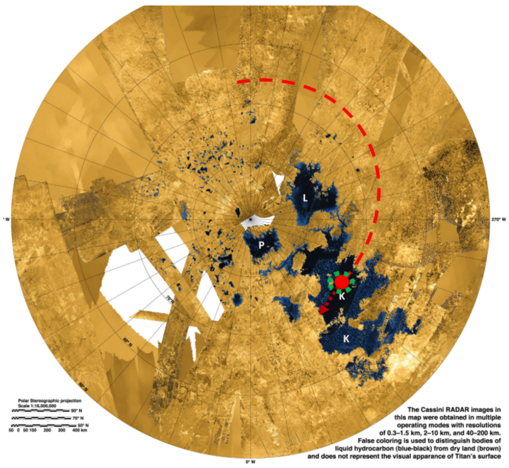

Figure 8: Kraken mare landing and ellipse of uncertainty of ± 50 km.

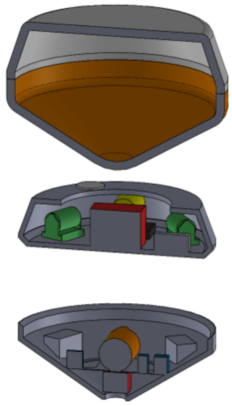

Figure 9: Lander Design

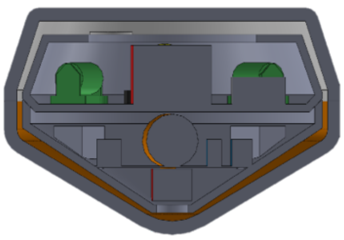

Figure 10: Lander design

COLUMBUS has two main parts, that carry an array of different scientific instruments. To see the variety of the scientific experiment, here is a list of the mounted instruments on the lander's upper buoy: Nephelometer, Camera, Water temperature sensor, Air temperature sensors, Relative humidity sensor, Thermal infrared sensor, Wind Sensor 1 and 2, Instrument control unit and pressure sensor, Atmospheric structure, Instruments, Tilt sensor. Data received through the measurements will be transmitted via X-Band and X-Band helical antenna to the orbiter.

Lander's lower buoy will have other instruments and sensors compared to the upper buoy. These are the following: Temperature sensor, Dielectric constant sensor, Pressure sensor, Gas Chromatograph-mass spectrometer and Sonar. The power system is designed to generate, store, and distribute energy to the lander at all stages of its life. For a 10 day mission, primary batteries are an obvious energy source: in this case, again $LiSO_2$ batteries. The battery mass will be about 6.5 kg. It will have a capacity of 2900 Wh to satisfy the power needs even in the worst scenario, with a peak power consumption of 150W.

8 Programmatic Considerations

A schedule has been developed to ensure the mission undergoes the phases from 0+A—F according to the ECSS-M-ST-10C standard. Making rough estimates and comparing the mission to heritage gave an educated guess of the mission's price, which comes out to €2.7B, of which €200M can be offset to member states. The probe accounts for €500M, and the lander accounts for €500M.

One of the key advantages of the mission is that while using a lot of instruments producing possibly great scientific output, most instruments that are used have Technology Readiness Level (TRL) higher than six. Only two instruments (Sonar and Tunable Laser Spectrometer) are of TRL ≤ 4. This is due to the heritage of former missions like Galileo and Cassini. However, a critical point is the development of the Thermal Control System (TCS) of the lander and the overall structure of the lander. The expected TRL are one respectively two. This is due to the highly differentiating needed temperatures as discussed in section 7.

It is common for space exploration missions to reduce the number of instruments on board due to financial or engineering difficulties. To prepare for this de-scoping process, the strongest links have been identified regarding which instruments are most vital to the mission and which give rise to demanding complexity, thermal and size requirements. It has been determined that reducing the number of instruments on either the lander or probe will have a minor impact on the mission's price, reducing the engineering challenge. This led to de-scoping options, such as outsourcing the development of the probe, lander, or both to either JAXA, NASA. The prioritisation analysis identified the probe as the least essential S/C segment, which is the first that will be removed.

9 Conclusions

SEAFARER provides an ambitious, challenging and educational platform for studying habitable environments in the

Saturnian system. Combining the probe VESPUCCI, the lander COLUMBUS, and the orbiter COOK is an optimistic proposal that has never flown before due to technological limitations. Nonetheless, with the latest developments in the space industry, such as the increased payload capacity of the Ariane 64 EVO and the heritage coming from memorable missions like JUICE and Cassini-Huygens, SEAFARER can be a unicum in the history of deep space exploration. This crucial step will permit an extensive study of Saturn, Enceladus, Mimas and Titan, searching for possible forms of life in these bodies, answers to the deepest mysteries of the formation of the Solar System, and ultimately pushes to the boundaries of humankind's knowledge.

References

1. Raymond, S. N. & Morbidelli, A. The Grand Tack model: a critical review. *Proceedings of the International Astronomical Union* **9,** 194–203 (2014).
2. Helfenstein, P. & Porco, C. C. Enceladus'geysers: relation to geological features. *The Astronomical Journal* **150,** 96 (2015).
3. Hsu, H.-W. *et al.* Ongoing hydrothermal activities within Enceladus. *Nature* **519,** 207–210 (2015).
4. Sekine, Y. *et al.* High-temperature water–rock interactions and hydrothermal environments in the chondrite-like core of Enceladus. *Nature Communications* **6,** 8604 (2015).
5. Schoenfeld, A. M. *et al.* Particle entrainment and rotating convection in Enceladus' ocean. *Communications Earth & Environment* **4,** 28 (2023).
6. Waite, J. H. *et al.* Cassini finds molecular hydrogen in the Enceladus plume: evidence for hydrothermal processes. *Science* **356,** 155–159 (2017).
7. Postberg, F. *et al.* Sodium salts in E-ring ice grains from an ocean below the surface of Enceladus. *Nature* **459,** 1098–1101 (2009).
8. Crow-Willard, E. N. & Pappalardo, R. T. Structural mapping of Enceladus and implications for formation of tectonized regions. *Journal of Geophysical Research: Planets* **120,** 928–950 (2015).
9. Postberg, F. *et al.* Detection of phosphates originating from Enceladus's ocean. *Nature* **618,** 489–493 (2023).
10. Lainey, V. *et al.* A recently formed ocean inside Saturn's moon Mimas. *Nature* **626,** 280–282 (2024).
11. Zandanel, A. *et al.* Geologically rapid aqueous mineral alteration at subfreezing temperatures in icy worlds. *Nature Astronomy* **6,** 554–559 (2022).
12. Běhounková, M. *et al.* Tidally induced magmatic pulses on the oceanic floor of Jupiter's moon Europa. *Geophysical Research Letters* **48,** e2020GL090077 (2021).
13. Hörst, S. M. Titan's atmosphere and climate. *Journal of Geophysical Research: Planets* **122,** 432–482 (2017).
14. Hayes, A. G. The lakes and seas of Titan. *Annual Review of Earth and Planetary Sciences* **44,** 57–83 (2016).
15. Hayes, A. G., Lorenz, R. D. & Lunine, J. I. A post-Cassini view of Titan's methane-based hydrologic cycle. *Nature Geoscience* **11,** 306–313 (2018).
16. Goossens, S., van Noort, B., Mateo, A., Mazarico, E. & van der Wal, W. A low-density ocean inside Titan inferred from Cassini data. *Nature Astronomy,* 1–10 (2024).
17. Rodriguez, S. *et al.* Science goals and new mission concepts for future exploration of Titan's atmosphere, geology and habitability: titan POlar scout/orbitEr and in situ lake lander and DrONe explorer (POSEIDON). *Experimental Astronomy* **54,** 911–973 (2022).
18. Coates, A. J. Interaction of Titan's ionosphere with Saturn's magnetosphere. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **367,** 773–788 (2009).
19. Lellouch, E. *et al.* The distribution of methane in Titan's stratosphere from Cassini/CIRS observations. *Icarus* **231,** 323–337 (2014).
20. Robinson, T. D. & Salvador, A. Exploring and validating exoplanet atmospheric retrievals with solar system analog observations. *The Planetary Science Journal* **4,** 10 (2023).
21. Kminek, G. *et al.* COSPAR policy on planetary protection. *Space Research Today* **208,** 10–22 (2020).
22. Rocchi, A. & Khan, M. Solar Electric Propulsion Boosted Transfers to the Outer Solar System. *preprints* (2023).
23. Strange, N. *et al.* *Mission design for the Titan Saturn system mission concept* Jan. 2010.
24. Vaquero, M. & Howell, K. C. Transfer design exploiting resonant orbits and manifolds in the Saturn–Titan system. *Journal of Spacecraft and Rockets* **50,** 1069–1085 (2013).