The ETNA Mission Concept:
Assessing the Habitability of an Active Ocean World

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Supplementary Material

1 Supplementary Data: Mission Budgets

The orbiter ΔV budget is 5.6 km/s with 5% margin on each maneuver to account for our pre-Phase A preliminary design of ETNA (Table 4 in the Main Text). Note that the interplanetary and pump-down maneuvers are presently not optimized, and a certain margin of improvement is expected. The orbiter would require 4025.56 kg of propellant (see Sec. 8.1.7 in Main Text for fuel and oxidizer masses).

The lander has a ΔV budget of 400 m/s. We applied a higher 20% margin to this budget given that the landing maneuver strongly depends on the landing site, which could be adjusted during orbital operations. We budgeted 36.5 kg of hydrazine for the lander.

2 Supplementary Data: Risks and Mitigation Strategies

We assessed various mission risks (2.1) and implementation risks (2.2) in accordance with guidelines from NASA's Independent Verification and Validation program (Northey and Kinney, 2014) and identified various pathways to mitigate and minimize these risks.

2.1 Mission Risks

Inability to achieve an aerobraking gravity assist trajectory. Given the need for novel aerogravity assists in the Saturnian system, inadequate upper atmosphere knowledge could lead to high uncertainty in the exit trajectory after the gravity assist. The preventable action was to design a conservative aerobraking protocol. The ETNA orbiter could perform an aerogravity assist at high altitude to improve the atmospheric model. Then, it could lower its altitude to perform a more breaking maneuver at lower altitude when the atmosphere's models are more detailed.

Experiencing contamination during Titan gravity assists. Given that Titan's atmosphere is rich in organics, it is important to assess how this contamination influences the analysis of data collected at Enceladus. To mitigate this risk, a thorough analysis should be performed to understand the impact of Titan-materials on the science return. Moreover, alternative approaches should be studied to reduce the spacecraft velocity and enable orbit insertion at Enceladus, such as the one proposed for the Orbilander mission (MacKenzie et al., 2020).

Experiencing instrument damage during plume fly-throughs. Given that star sensors, UVIS, and OICAM lack a physical shutter, flying through the plume when sampling may cause instrument damage that could reduce science return and interfere with attitude determination. The mitigation action was to fix these instruments on the spacecraft to face opposite of the attached lander, i.e., the direction of the spacecraft during fly-through sampling. Moreover, plume sampling operations were scheduled at the end of the orbiter science phase to reduce risk.

Inability to land safely through autonomous operations. Given the need for autonomous landing, premature GNC algorithms (low TRL) could lead to landing anomalies. However, terrain relative navigation (TRN) algorithms in addition to other control methods are being widely developed and improved by NASA (e.g., AHALT, OSIRIS-REx). It is expected that by the time of the landing, mature GNC algorithms will be available both from other missions' heritage and from ETNA development plans.

Inability to land safely in challenging illumination conditions. The vision-based landing system requires illuminated terrain to perform hazard detection and avoidance (HDA). The mitigation taken during the mission design was to select a launch date that ensures illuminated south polar terrains up to 1 January 2041. Moreover, a LiDAR was added to the landing suite for obtaining topographic measurements at lower altitudes; the LiDAR does not require any illumination. Alternative landing instruments utilizing other wavelengths, such as radar (Konstantinidis et al., 2015), could also be developed, although they are not included in the current payload design.

Inability to land safely on terrains of unknown strength. ETNA requires landing nearby an active plume to collect plume materials. If the landing site is relatively soft, then the landed laboratory could have a non-nominal orientation and/or sunken legs. To mitigate these risks, the landed laboratory was designed with large and buoyant feet (Fig. 6C in Main Text) that minimize the force on the soil, thus increasing the probability of an upright landing.

Inability to acquire high-quality geophone measurements. The SHOOC probes should be deployed on a hard surface for high-frequency readings close to the plumes. Landing on a soft surface would adversely impact their ability to acquire high-frequency readings. To mitigate this risk, the SHOOC probes would be distributed to different locations to increase the likelihood of impacting hard surfaces. This risk was minimized by using three SHOOC probes whereas the minimal set for triangulating the signal is two.

2.2 Implementation Risks

Delay in instrument availability. Given the use of heritage instrumentation, the lack of stock/production capability from the manufacturer would prevent the instrument from being used on the mission. This risk would be mitigated by entering discussions with manufacturers early in the design process to agree on a schedule for planning and delivery.

Inability to progress the TRL of SHOOC probes. Unexpected challenges could lead to cost overrun and premature development at launch. The preventable action was to design a stand-alone system, which could be removed from the mission design if not mature, without drastically affecting science return. The SHOOC probes could be proposed as a technology demonstration, and threshold science would not suffer with their exclusion.

Delay in RTG availability. Given the need for an RTG-based power source, the low-maturity of this technology would impact overall mission leading to delays. On the one hand, the MMRTG carried by the orbiter has similar characteristics to the one carried by Curiosity (Woerner et al., 2013), which has a TRL of 9. On the other hand, the MMRTG carried by the lander is still under development by NASA and the U.S. Department of Energy for other mission concepts (Woerner, 2017). This increases the possibility of a mature technology at launch time both from other missions' heritage and from ETNA development plans. It is worth noting that the overall power consumption of the two MMRTG modules is about 360 W at BOL, which is half of the power generated by Cassini's RTG module (Johnson and Cockfield, 2005) and less than the power generated by two RTGs carried by Voyager 1 and Voyager 2 (Woerner, 2017). It is thus reasonable to assume that, despite MMRTG program anomalies, it is feasible to obtain the MMRTG module in time for the proposed mission.

Delay in launcher development. Delays related to SLS development could affect the mission schedule. We mitigated the risk of an upset mission timeline because the ETNA spacecraft could also be launched with alternative, mature launchers (Sec. 7.1 in Main Text). Furthermore, the mission design is robust to delays in arrival date (Sec. 7.1 in Main Text), and science goals could still be achieved if arrival is postponed. Even if ETNA arrives in darkness, all scientific payload would operate with full capabilities, with the exception of OICAM. Threshold science could still be met.

2.3 Planetary Protection Risks

Another programmatic concern to assess programmatically is planetary protection, due to the Class IV nature of landing at Enceladus (COSPAR, 2021). The lander and the SHOOC probes, which would be in direct contact with the Enceladus surface, must be carefully sterilized (4 to 6 log reduction). The orbiter, which would stay in contact with the Enceladus plumes during fly-throughs, would require a lighter sterilization process (2 to 3 log reduction). The sterilization process used for the bioburden control involves dry-heat microbial reduction (DHMR), UV Sterilization and Gamma Sterilization. The dry heat microbial reduction is the preferred sterilization process adopted owing to its efficiency in sterilizing heat resistant microbes. Critical elements where heating poses a significant detrimental impact, UV-sterilization and gamma sterilization is adopted.

The orbiter disposal maneuver is critical for possible impact on Enceladus or Titan, and numerical simulations indicate an orbital disposal impact at Saturn can occur successfullywith 99% probability.

3 Supplementary Figures

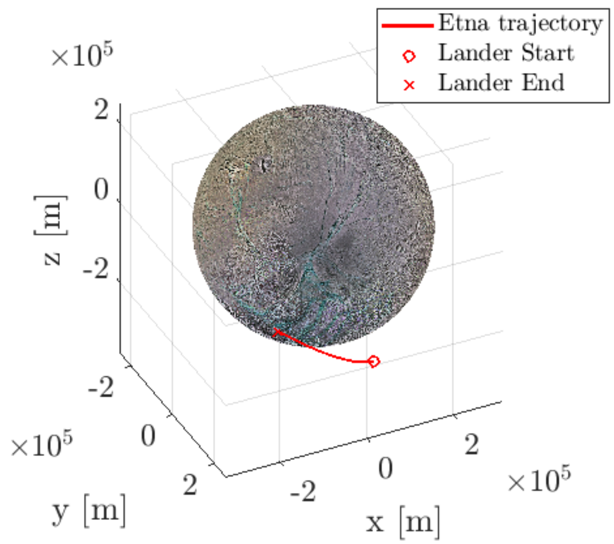

Figure S1. The ETNA landing trajectory is traced in red, starting from a spacecraft altitude of 150 km (red circle), landing at the south polar region (red "X").

4 Supplementary Tables

Table S1. Mass budget of the orbiter. The lander is excluded.

Subsystem	Mass (kg)
Instruments	70.9
GNC	19.4
Power	150
Thermal	10
On-Board Data Handling	13
Communication	115.5
Structure	50.42
Propulsion	125.4
Total Dry Mass (Excluding Lander)	554.92

Table S2. Evaluation of trades between RTGs and solar panels considered in the selection of the ETNA orbiter power generation. Values 1 (low) to 5 (high) rank the criticality of various trade qualities. The total score is computed as the sum of the individual score per trade quality weighted on the criticality value.

		Orbiter Considered Power System	
Trade Quality	**Criticality**	**RTG**	**Solar Panels**
Power	5 – High	4 – Very Good	1 – Poor
System Mass	3 – Medium	2 – Fair	2 – Fair
Complexity/TRL	5 – High	4 – Very Good	4 – Very Good
Cost	3 – Medium	2 – Fair	4 – Very Good
Impact on other subsystems*	5 – High	4 – Very Good	1 – Poor
Planetary Protection	5 – High	1 – Poor	5 – Excellent
Total Score	--	77	73

*Increase in orbiter subsystems mass other than the power subsystem

Table S3. Estimated temperatures (°C) for the hub interior, and hottest and coldest exterior faces of the orbiter simulated for "cold" and "hot" cases, both with and without MMRTG thermal power. "Cold" cases are defined as the further distance from the Sun while the orbiter is shadowed. "Hot" cases are defined as the closest distance to the Sun while the orbiter is illuminated. It is considered that the MMRTG provides 2000 W of thermal power.

Case	Hub Interior (°C)	Hottest Exterior Face (°C)	Coldest Exterior Face (°C)
Cold Case without MMRTG thermal power	-147.45	-137.46	-153.79
Hot Case without MMRTG thermal power	-134.42	-126.49	-138.38
Cold Case with MMRTG thermal power	26.93	13.26	11.8
Hot Case with MMRTG thermal power	28.04	14.56	13.3

Table S4. Mass budget of the lander.

Subsystem	Mass (kg)
Instruments (SHOOC probes included)	68.5
GNC	9.1
Power	29
Thermal*	5
On-Board Data Handling	2.6
Communication	5.2
Structure	13.4
Propulsion	14.6
Total Dry Mass	147.4
Mass consumables	36.5
Total Wet Mass	183.9

*Batteries included in the power subsystem.

Table S5. Evaluation of trades between RTGs, solar panels, and batteries considered in the selection of the lander power generation. The total score is computed as the sum of the individual score per trade quality weighted on the criticality value.

		Considered Power System		
Trade Quality	Criticality	RTGs	Solar Panels	Batteries
Power	5 – High	4 – Very Good	1 – Poor	3 – Good
Mass	3 – Medium	2 – Fair	2 – Fair	3 – Good
Complexity/TRL	5 – High	4 – Very Good	4 – Very Good	4 – Very Good
Cost	3 – Medium	2 – Fair	4 – Very Good	4 – Very Good
Operation Length	5 – High	5 – Excellent	1 – Poor	3 – Good
Planetary Protection	5 – High	1 – Poor	5 – Excellent	5 – Excellent
Impact on Thermal Subsystem	4 – Moderate	5 – Excellent	1 – Poor	3 – Good
Total Score	-	102	78	105