TIGER: JPL PSSS Architecture and Feasibility Study for a New Frontiers 5 Mission Concept to Enceladus.

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Introduction: The Cassini-Huygens mission opened the scientific community's eyes to the unique nature of Saturn's satellite, Enceladus. It confirmed Enceladus has a global, liquid water ocean [1] [2], active jets emanating from its southern pole [3] containing complex organic material [4], and a geologically young surface in the southern hemisphere [5]. Making these discoveries all the more intriguing is Enceladus' relatively small size compared to other confirmed ocean worlds [6]. Since the Cassini-Huygens mission, no mission has re-visited this potentially habitable ocean world despite it being a priority target for the 2013 Decadal Survey [7], and New Frontiers (NF) 4. The Committee on Astrobiology and Planetary Sciences (CAPS) recommended Enceladus as a prioritized target for the NF 5 call [8].

This work examines a conceptual NF-class mission to Enceladus, TIGER, to characterize habitability of Enceladus' ocean. Challenges associated with a NF-class mission to Enceladus are discussed, and possible solutions with tradespaces are posited.

Science Objectives: The primary goal of the TIGER mission would be to examine the habitability of Enceladus' ocean. First, TIGER would assess the potential for habitability of the subsurface ocean by analyzing plume ejecta believed to originate from the bulk ocean [2] to assess the potential for habitability of the subsurface ocean. Second, understanding how the plume material may be processed or altered as it ascends through the ice shell and is ejected from the surface is addressed. These are expressed as the following science objectives:

1. Determine if Enceladus' volatile population undergoes synthesis of complex organic species that are evidence for a habitable ocean.
2. Determine whether Enceladus' plume material is supplied directly from the ocean or if it interfaces with other reservoirs within the ice shell.

To address objective 1, the presence of the building blocks for life (defined as complex/high mass organic compounds e.g., larger than alanine, 90 amu), the abundance of ions (Na, Mg, Ca), H_2, sulfur, and silicate which were previously detected by Cassini [9] would be assessed. This is achieved through mass spectra and UV spectra to measure the presence and abundance of these compounds.

For the second objective, understanding how the plume material is altered through the ice shell requires knowledge of the ice shell's physical properties. These properties include the distribution, width, shape, and length of the plume vent conduits and fractures within the ice shell. These are determined through measuring the dielectric constant of the surface and performing spatial correlation to determine the thickness of the ice. The distribution, shape, and other dimensions would be determined via radargrams collected with ground penetrating radar.

Payload: Based on the observables for the listed objectives, the required instruments include a mass spectrometer, ultraviolet spectrometer, radar, and a context camera. Thorough analysis was performed with published instrument concepts for appropriate analogs, like MASPEX, P-ALICE, REASON, and Dawn Framing Camera, respectively. Table 1 shows the instrument requirements.

Table 1: TIGER science objectives achievable with corresponding instrumentation.

Science Objective	Physical Parameter	Mass Spec	Radar	UV Spec	Camera
1	1.1 Determine whether key building blocks for life exist in Enceladus' ocean.	✓			
	1.2 Abundance of H2, ions (Na, Mg, Ca), sulfur, and silicate indicative of redox state of Enceladus' interior.	✓		✓	
2	2.1 Ice shell thickness.		✓		✓
	2.2 Distribution, shape, width, and length of plume vent conduits/fractures within the ice shell.		✓		✓

Mission Architecture: TIGER would launch in June 2029 and utilize a Venus-Earth-Earth gravity assist trajectory (to reduce fuel mass) to arrive at Saturn in March 2038. The interplanetary cruise time is 8.8 years, the orbit adjustment time after Saturn orbit insertion is 0.8 years, and the science phase is 1.2 years. Seven flybys of Enceladus via Saturnian orbit would provide enough data to fulfill our science objectives and an additional contingency flyby is also included for a total of eight flybys. At the conclusion of the mission, the spacecraft would be disposed of into Saturn.

The baseline TIGER spacecraft has a launch mass of 2,410 kg. It is three-axis stabilized using reaction wheel assemblies (RWAs), would be powered by two Next-Gen RTGs, and has a liquid bipropellant propulsion system for trajectory correction maneuvers and station keeping. The NASA Deep Space Network (DSN) would be used to communicate with the spacecraft, with science data stored using the next-generation Sphinx command and data system [10] and downlinked using an X-band system during loitering periods. The two Next-Gen RTGs would be mounted at the base of the spacecraft, balanced 180° apart, similar to the RTG mounting configuration on Cassini. Sun shields protect the RTGs during the Venus flyby. Above the engine and the RTGs, the spacecraft is split into two modules: a propulsion module containing propellant tanks and RWAs and an avionics module containing batteries, attitude sensors, electronics, and instrumentation. Three of the instruments are mounted in the nadir pointing direction. The high gain antenna (HGA) for telecom is mounted to the top of the spacecraft. Radiators, multi-layer insulation, a pumped fluid loop, and radioisotope heater units would be used to ensure spacecraft temperature limits are not exceeded.

Trades and Challenges:

1. Trades

(1.a) Our science objectives focus on habitability to constrain environmental context to better equip future life detection missions. This allowed us to remain within NF-class mission constraints, compared to more costly life detection driven objectives. Thus, we prioritized constraining environmental context through habitability objectives that future life detection experiments can use to select more specific instrument payloads and scientific objectives.

(1.b) An Enceladus orbiting mission architecture was initially explored to answer a larger number of science questions, but was found to be likely to exceed cost, mass, and power limits associated with a NF-class mission. However, TIGER's architecture as a flyby mission would still support scientific data collection commensurate with a NF-class mission.

(1.c) Designing an adequate power system was a significant challenge for this mission concept. Two Next-Gen RTGs were selected as the baseline power system, given that MMRTGs and potential eMMRTGs did not have sufficient performance, and solar arrays of a manageable size are not expected to be able to provide enough power.

2. Challenges

(2.a) The January 2039 Enceladus equinox is a concern for missions that require visual images of the surface. Starting in January 2039, an increasing amount of the South Polar Terrain (SPT) of Enceladus, where the plume is located, would enter many-year periods of shadow. This mission requires a relatively small number of visual images of the SPT and the flyby architecture enables flybys to occur relatively soon after Saturn orbit insertion, so this challenge is less impactful for TIGER than it might be with alternative mission concept designs.

(2.b) Enceladus flyby speeds must be managed such that each instrument can successfully collect necessary data. If the sample entering the mass spectrometer is too fast, critical samples may be lost [11]. Meanwhile, radar velocity is capped by the round-trip time of the radar beam given its design per prior environmental knowledge.

(2.c) Our instruments fall in the mid-TRL (Technology Readiness Level) range, as do many of the projected ocean world instrument needs [12][13]. Targeted investment in the advancement of ocean world and life detection instruments and technologies would need to be prioritized over the coming decade to facilitate TIGER's mission timeline. TIGER does, however, have significant cost reserves available to help mitigate this mission risk.

TIGER is a compelling mission architecture that would answer important habitability questions about Enceladus. The development of our mission concept directly contributes to future ocean worlds missions. As has been motivated by multi-decadal surveys, significant scientific understanding of ocean worlds can be built upon over the course of multiple missions to Enceladus [14].

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