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Assessing the need for a distributed sensor network at Enceladus: We are working to establish the most effective mission architecture among competing options—multiple flyby, orbiter, landed assets—to address the key outstanding geophysical questions about Enceladus that have an astrobiological bearing. A future mission to look for indications of life on Enceladus must be the result of a careful survey to select the most effective scientific investigations. While this survey should be agnostic of the chosen mission architecture, it is important for context to consider the merits of different options, alone or in concert.

The context of sampled materials will be key to understanding any potential biosignatures. Placing collected samples in context requires further knowledge of the interior of Enceladus. For example, a putative biosignature in the form of a mass distribution of hydrocarbons consistent with life on Earth must be interpreted in light of the inferred mineral composition, vigor of water-rock alteration through time, and corresponding inferred fluxes to the ocean of reductants and oxidants that create the energetic chemical conditions for different metabolic reactions.

Key contextual questions addressed by geophysical measurements to assess the astrobiological potential include:

1. How is tidal dissipation distributed between the icy crust [2], ocean [3, 4, 5], or rocky core [6]?
2. Why does the North Pole differ from the South Pole?
3. What is the spatial occurrence of ongoing high-temperature water-rock interactions [7,8,9,10].
4. What is the resurfacing rate?
5. What is the rate of delivery of any oxidants to the interior [11]?
6. How are materials at the ice-ocean interface fractionated ice formation and melt processes, and by the workings of the eruptive south polar plumes?
7. How, and to what extent, does the ocean transport materials to the ice-ocean interface and toward the icy surface?

Of prime interest are the merits of a landed *in situ* mission relative to a multiple-flyby or orbiter design. Different geophysical techniques can be used to address the science questions. This study investigates how well these techniques can address the science questions. This will further lead to requirements on the mission architecture.

Diverse geophysical investigations are being explored to address these science questions. For each of them, this study performs forward modelling of end member cases constrained by the *Cassini* observations. Numbers in parentheses below correspond to the science questions addressed.

Gravity, libration, tilt, surface displacement *(1,2,3)*: The ice shell thickness variations and mechanical properties of the rocky core can be assessed by measuring the static low-degree gravity potential and its time variations. Assuming a gravity signal of tens of micro-Gal [12,13; Fig. 1] and a tidal Love number k_2~0.03, it is not possible to measure the diurnal response of Enceladus with multiple flybys. An orbiter mission is the best way to achieve such measurements. A single- or even multiple-flyby mission with closest approach of 100 km at relative surface velocities V>5km/s would not be sufficient for measuring the degree-2 variation gravitational potential because the corresponding velocity perturbations ($\Delta v \sim 2r\Delta g/V$) would be in the range of tens of μm/s or even less. By contrast, the perturbations sensed by an orbiter (V<0.2 km/s at 100 km) would be measurable by currently available radio science subsystems.

A 30-day orbiter mission could map the static gravity field anomaly associated with ice-shell thickness and estimate time variations of the low-degree coefficients. However, circular polar orbits around Enceladus are unstable; to avoid constant maneuvering requires a non-circular orbit with a lower inclination [e.g., 14]. Such an inclined and eccentric orbiter would still be able to infer the low-degree static field and its time variations. GRAIL-type mission profiles are not required.

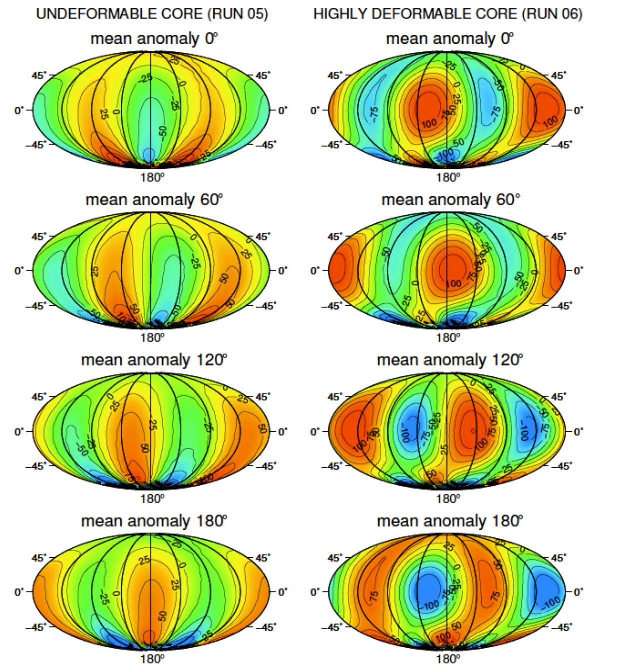
InSAR, LiDAR, Thermal/Topographic Mapping *(1,2,4,5,6)*: Repeat-pass synthetic-aperture radar (InSAR) or LiDAR altimetry passes over the same terrains would allow interferometric analyses to constrain the horizontal and vertical motions of ice and opening of fissures where plume jets originate; help detect active rifts and the presence of grounded areas; and provide constraints on deriving the thickness of the icy crust [15]. A dedicated InSAR investigation could collect measurements with millimeter precision versus tens of cm from LiDAR [16]. Laser altimetry would have the advantage of aiding a gravity investigation. Mapping topographic features and thermal output with greater spatial coverage and resolution than *Cassini*'s investigations would facilitate understanding of the heat distribution and active features in the ice.

Electromagnetic Sounding *(2,3,6,7)*: In contrast with Jupiter, no tilt of Saturn's intrinsic magnetic field with respect to its spin axis has been observed [17]. Nevertheless, it may be possible to infer the ocean thickness and conductivity from externally excited oscillations of the magnetic field [18].

Seismology could address all seven questions. It would be the best technique for resolving the interior structure of Enceladus, and would be highly complementary to the techniques described above thanks to its ability to measure the moon's dynamics on time scales that are not resolvable from orbit. We are exploring the trade-space between the number of seismic nodes, seismometer sensitivity, and mission duration needed to characterize the thickness and dynamics of the ice, any fluid layers therein; the thickness, heterogeneity, and dynamics of the ocean; and the nature of the underlying rocky interior [19,20,21,22]. The moon's small size means that a single seismometer has a strong likelihood of detecting signals originating anywhere on or within Enceladus, while the significant observed plume activity likely indicates ample seismicity as sources for passive seismic techniques. A multi-seismometer investigation with nodes around plume sources could provide important information about the mechanics of observed fissures as well as fluid and gas movement in the region of the south polar plumes.

Candidate mission designs: A combination of the above methodologies would advance our understanding of the workings and possible habitancy of Enceladus. Prior mission studies provide a starting point for considering a distributed network of small spacecraft. The mission design and instrument suite for the *Europa Clipper* concept provides mapping coverage and geophysical fidelity generally exceeding those of *Cassini* [23]. A subset of comparable instruments could be deployed at Enceladus [24]. Concepts for landed missions on icy moons demonstrate the plausibility of safely landing an autonomous laboratory for biosignature characterization and geophysics [25,26].

Figure 1. Calculated tidal response including surface topography, ice thickness variations, and faults [12]. The panels on the left show a model with an undeformable rocky core at four different orbital phases. The panels on the right show the same model, but with a deformable rocky core. The contour interval is 25 μGal.



References: [1] Kempf S. et al. (2010) *Icarus*, 206, 446-457. [2] Nimmo F. and M. Manga (2009). *Europa*, U. of Arizona Press, Tucson, 381. [3] Tyler R. (2014) *Icarus*, 243(0), 358-385. [4] Matsuyama I. et al. (2018) *Icarus*, 312, 208-230. [5] Rovira-Navarro M. et al. (2018) *Icarus*, 321, 126-140. [6] Choblet G. et al. (2017) *Icarus*, 285, 252–262. [7] Hsu H.-W. et al. (2015) *Nature*, 519(7542), 207–210. [8] Sekine Y. et al. (2015) *Nature Comm.*, 6. [9] Postberg F. et al. (2018) *Nature*, 558(7711), 564–568. [10] Glein C. R. et al. (2018). *Enceladus and the Icy Moons of Saturn*, U. Arizona Press, Tucson, 39. [11] Vance et al. (2016) *GRL*, 10.1002/2016GL068547. [12] Běhounková M. et al. (2018) *Astrobiology,* 17(9), 941–954. [13] Čadek et al. (2019) *Icarus,* 319, 476–484. [14] Strange N. et al. (2009) AGU Fall Meeting abstracts P42A-05. [15] Sandwell D. et al. (2004) *JGR*, 109, E11003. [16] Rignot E. et al. (2011) *Science*, 333(6048),1427–1430. [17] Dougherty et al., (2018), Science [18] Saur J. et al. (2009) *Space Science Reviews*, 152(1-4), 391–421. [19] Vance S. et al. (2018) Astrobiology, 18(1), 37–53. [20] Vance S. et al. (2018) *JGR-Planets*, 180-205. [21] Panning P. et al. (2018) *JGR-Planets* 123(1), 163–179. [22] Stähler S. et al. *JGR-Planets* 123(1), 1-27. [23] Lunine J.I. et al. (2015) *LPSC* 1525. [24] Buffington B. et al. (2017) *Proc Int Astronautical Congress* IAC-17-C1.7.8. [25] Konstantinidis K. et al. (2015) *Acta Astronautica* 106, 63-89. [26] Hand K. et al. (2017), *JPL* D-97667.