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Enceladus' Subsurface Secrets: Scientific Rationale for Future Radar Sounder Measurements

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An outstanding question in planetary exploration addresses the habitability of icy moons in the outer Solar System. These bodies can harbor liquid water in substantial amounts over long time-scales, a necessary ingredient for habitable environments (Nimmo, 2018). Water on icy moons is located in a subsurface ocean covered by a global ice shell, and/or in local reservoirs within the ice shell itself. Moreover, for some of the satellites, in particular Europa and Enceladus and perhaps also Triton and the largest moons of Uranus, their oceans are in contact with the silicate interior. This allows for water-rock interactions potentially similar to those at the ocean floor on Earth. Such interactions would bring chemical compounds, in particular Carbon, Hydrogen, Nitrogen, Oxygen, Phosphorus, and Sulphur (CHNOPS) in contact with liquid water, creating the 'right' chemistry for a habitable environment. Due to tidal friction, which can be an important heat source in the moons' interiors, energy that drives chemical cycles would be available and sustained over time, providing stable conditions for thermal and chemical reservoirs over billions of years.

Among the icy moons, Enceladus has been recommended as the top priority target in ESA's Voyage 2050 plan covering the science theme "Moons of the Giant Planets" (Martins et al., 2024), because of its high astrobiological potential. Based on the current knowledge from mission data and theoretical modelling, Enceladus provides compelling evidence for habitable conditions. The presence of a global ocean is supported by the combined analysis of low-order gravity field and topography data (Iess et al., 2014), and by independent measurements of forced physical librations (Thomas et al., 2016). The subsurface ocean is kept in a liquid state due to tidal energy that represents an important source of heat in Enceladus's interior. Tidal deformation is also thought to drive the water plume activity at Enceladus' south pole that was observed by the Cassini spacecraft (Porco et al., 2006). Constraints on the composition of Enceladus' ocean and ice chemistry come from the plume material sampled during NASA's Cassini mission, suggesting that within the ocean and ice, chloride and carbonate salts, as well as ammonia/ammonium and silica are present, the latter with lower concentrations (Postberg et al., 2018). The detection of nanometer-size silica grains in Enceladus' plume material supports the presence of high-temperature hydrothermal alteration that is thought to occur at the ocean floor (Hsu et al., 2015). Moreover, local topographic depressions observed by Cassini using stereo imaging analysis could indicate the presence of regional liquid water reservoirs at shallow depths (Shenk & McKinnon, 2009).

A subsurface radar sounder has been suggested to be part of the core payload of a future mission to Enceladus (Martins et al., 2024), as radar sounders are the obvious means to detect and characterize subsurface water reservoirs in the interior of icy moons (Benedikter et al., 2022). The scientific goals for radar sounder measurements on icy moons can be summarized as follows:

- Detection of global oceans by determining the ice-water interface and the spatial variation of the ice layer thickness

- Detection of near-surface water reservoirs that could be embedded in the ice shell
- The study of dynamic processes at active regions, in particular the connection of the ocean with the shallow subsurface/surface
- Characterization the layering of the upper ice crust, e.g. snow, ice regolith, compact ice for determining the past evolution (intensity of jet activity and geological history)

In this study we focus on the scientific goals of a radar sounder at Enceladus. We discuss the ice shell characteristics (thickness and variations, thermal structure, and layering) and their effects on the radar attenuation. We calculate the two-way radar attenuation on Enceladus considering a porous thermally insulating surface layer generated by the plume material that falls back onto Enceladus' surface. Our models show that for regions with a thin ice shell, most likely in a thermal conductive state, such as the south pole of Enceladus, the ice-ocean interface is detectable independent of the ice shell composition (Byrne et al., 2024). In regions covered by a thick insulating porous surface layer as suggested at least regionally, by the analysis of pit chains on the surface of Enceladus (Martin et al. 2023) a radar signal will not be able to reach the ice-ocean interface. However, for these same regions the high subsurface temperatures caused by a strong insulation due to the thick porous layer increase the likelihood that shallow brines are present (Byrne et al., 2024). Such brine reservoirs are fundamental to characterize potential habitable environments in the shallow subsurface, and the potential to directly access them with future measurements is much greater when compared to the accessibility of subsurface oceans (Wolfenbarger et al., 2022).

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