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From Sea Ice to Icy Shells: Modeling the Dielectric Properties of Ice-Brine Mixtures

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The search for habitable worlds within our solar system is guided by liquid water. Evidence for global, salty oceans hidden beneath the icy shells of moons in the Jovian system has motivated two upcoming missions: ESA's Jupiter Icy Moons Explorer (Juice), launched April 2023, and NASA's Europa Clipper, launching October 2024. Both spacecraft are equipped with ice-penetrating radar instruments, the Radar for Icy Moon Exploration (RIME) and the Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON), that will transmit radio waves into the subsurface and record energy reflected from interfaces defined by contrasts in dielectric properties, such as the ice-ocean interface.

The ocean is presumed to be the most extensive liquid water reservoir beneath the surface. However, various ice-water interfaces could exist throughout the ice shell. Dynamic processes such as impacts, convection, tidal heating, strike-slip faulting, and basal fracturing have been hypothesized to influence melt generation or inject ocean water in the ice shell interior. Even in the absence of these dynamic processes, impurities within the ice allow liquid water to be thermodynamically stable as brine at temperatures below the freezing point. In ice shells with non-zero bulk salinity, transitions from solid ice to ice-brine mixtures, or eutectic interfaces, invariably precede the ice-ocean interface. Understanding the detectability and radiometric character of eutectic interfaces is therefore a critical step towards interpreting the data collected by these ice-penetrating radar instruments.

In this work, we review measurements and models of the dielectric properties of sea ice and marine ice on Earth. We use these measurements and models as a foundation to propose a path forward for modeling the dielectric properties of eutectic interfaces within an ice shell. We assess how the ice shell's bulk salinity and the thickness of the thermally conductive layer impact the detectability and radiometric characteristics of eutectic interfaces. Our discussion includes how future laboratory measurements of existing terrestrial ice samples coupled to measurements of proxy samples consistent with off-world ocean sources can inform and refine our proposed framework.