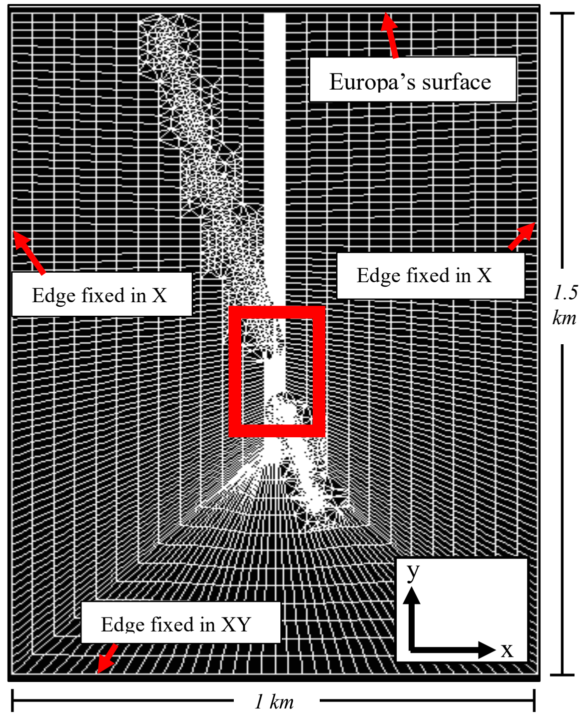
**Modeling Fracture Hazards at Europa for Cryobot Tunneling and Communication.** R. Lien[1], K. Craft[2], M. Walker, C. German[3], M. Jakuba[3], R. Lorenz[2], C. McCarthy[4], W. Patterson[2], A. Rhoden[5], M. Silvia[3], V. Singh[4,6]. [1]Montana State University, Bozeman, MT (rudi.lien@student.montana.edu); [2]Johns Hopkins University Applied Physics Laboratory, Laurel, MD (Kate.Craft@jhuapl.edu); [3]Woods Hole Oceanographic Institution, [4]Lamont-Doherty Earth Observatory, [5]Southwestern Research Institute – Boulder, [6]School of Earth and Space Exploration, Arizona State University.

**Introduction:** Icy ocean worlds are seemingly ideal locations in our solar system to search for extraterrestrial life. Jupiter's icy moon Europa appears to have an internal water ocean underneath a potentially 10s of kilometers thick ice shell [1]. While tidal forces provide the heat source necessary to maintain a subsurface ocean, they also produce fractures and tectonic features observed at Europa's surface that may extend to a depth of 1-3 km within the European ice shell [2-3]. The potential habitability of the subsurface ocean makes it an ideal candidate for future exploration, but a probe would need to drill or melt through the ice shell and be able to navigate cryotectonic hazards to reach the ocean. Communications will likely be dependent on a tether extending from the probe to the surface, so it is necessary to understand the potential hazards that the probe and tether could experience within the ice shell [4]. The estimated range for the thickness of Europa's ice shell varies from a few kilometers up to 70 km [5]. The 2019 Compass Final Report assumed that the ice shell is less than 20 km thick based on impact crater analyses, and therefore is the shell thickness assumed for this project [4, 6].

Here we present our work using two finite element modeling programs, FRANC2d (FRacture ANalysis Code) and Ansys Mechanical, to model fracture hazards at Europa in order to quantitatively characterize the stress and strain imposed by nearby surface faults on a melting cryobot and its communication tether. We also apply tidal stress data from models by Matt Walker to determine the effects that diurnal tidal bulging will have on pre-existing fractures within the European ice shell. This work is part of a larger project with the Europa Signals Through the Ice (STI) team, which is funded by NASA's SESAME program to explore and test communication techniques for an ice-ocean probe via numerical modeling and laboratory experiments.

**Model Set-up:** In the models presented here, the cryobot was at a depth of 1 km, the top of the geometry represented the surface of the ice shell, and material properties were homogeneous throughout the ice shell. The material properties include the Young's modulus = 5 GPa, Poisson's ratio = 0.30, and density = 920 kg/m$^3$; the values of these properties are within experimental ranges for pure water ice and have been used in previous studies to model Europa's ice shell [8]. Europa's gravitational body load of -1.3 m/s$^2$ was applied to the models. These parameter values were used for all the models described below.



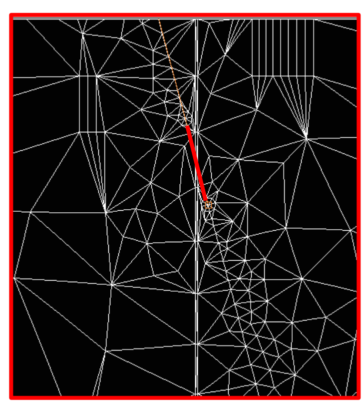



*Figure 1. a) Mesh representing 1-km by 1.5-km region of the European ice shell with a fracture disconnected by cryobot melting. b) Region outlined by red box in fig. 1a; red line shows line of propagation for the disconnected fracture tips as calculated by FRANC2d.*

*Two-Dimensional.* The FRANC2d program calculates displacements and the resulting stresses that are caused by applied loads, boundary conditions, and specified material properties in order to determine whether a fracture could initiate and propagate [7]. Our base model consisted of a 2-dimensional mesh with a 5.2-m-long by 0.5-m-wide void, which represented the cryobot, within a 1.5-km-long by 1-km-wide region of the ice shell (Figure 1a). The left and right sides of the void were held in the X direction to represent the presence of the cryobot. The cryobot dimensions were based on probe designs described in the 2019 Compass Final Report: Europa Tunnelbot [4]. Also, the models assumed a melt probe that would melt the ice beneath the probe and so produce a region behind it where the water would refreeze. This refrozen ice was represented in our models as a 0.5-meter-wide column, which extended from the top of the probe to the surface.

*Three-Dimensional.* Ansys Mechanical is an engineering software used for structural analysis. We designed a 3-dimensional geometry to represent a 3-km-long by 2-km-wide by 2.5-km-deep section of Europa's ice shell. We assumed a completely elastic shell of 10-km total thickness. All faces aside from the top and base of the ice block are fixed so that the block can only deform in the vertical direction at its boundaries; this fixity represents the continuation of the ice shell beyond the modeled block. A void representing the cryobot was included with dimensions the same as previously described: 5.2-m-long with a 0.5-m diameter, located at 1-km depth and centered horizontally.

**Initial Results:** The FRANC2d program was used to determine the stresses that a probe and communication tether could experience when one or more pre-existing fractures are proximal to the cryobot void. According to fracture mechanics theory, a fracture can form or propagate if tensile stresses are present and exceed the tensile strength of ice, $10^4 – 10^6$ Pa [8]. When a pre-existing fracture was crossed by the cryobot, tensile stresses exceeding the tensile strength of ice were observed at the separated fracture tips. Analysis within FRANC2d indicated that both fracture tips would subsequently propagate back towards each other (Figure 1b). This result implies that the pre-existing fracture could reconnect, and slip could occur along its edges causing strain on the communication tether.

FRANC2d did not have the capabilities to model and quantify slip displacement along a fracture, so we transitioned to Ansys Mechanical to investigate the effects of faulting on the communication tether. A fault plane oriented at 70 degrees below the horizontal and 930-m-long was inserted into the 3-dimensional geometry to represent the reconnected fracture from the FRANC2d model. Preliminary results indicated that a maximum of -60 cm of vertical displacement occurs from gravitational loading, which is constant in time and space. Analyses of displacement by tidal stress is in progress in order to model whether tidal stresses are great enough to induce fault slip. Deformation analysis within Ansys will indicate the displacements and strain across the communication tether resulting from a fault slip event. The cycle of tidal bulging on Europa is expected to potentially result in a back-and-forth motion along the fault, so we are working to model fault motion over the complete tidal cycle. We intend to model multiple locations on Europa – at maximum, minimum, and intermediate tidal bulging – in order to rank the hazard level, related to faulting potential and slip magnitude, of potential landing sites for future missions. Stress and strain values determined from these models will be used in laboratory experiments to test strength limitations of potential tethers, which are investigations being performed by other members of the Europa STI team (see abstract Singh et al., for this meeting).

**Significance:** The search for life beyond Earth continues to excite both scientists and the general public, and that excitement grows as we learn more about icy ocean worlds like Europa. However, the dynamic surface of Europa implies that the subsurface is impacted by active fracturing and tectonism that would make a subsurface mission difficult. The numerical modeling investigations being performed here are quantitatively characterizing the risks that a Europa cryobot could experience, and further laboratory experiments will be able to test the limitations of the current probe and tether designs based on the model results. These and additional results of this project will be useful and informative for future mission development of subsurface exploration at Europa or other icy ocean worlds.

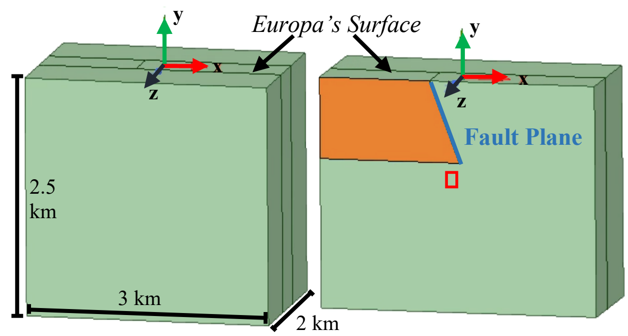



*Figure 2. 3-dimensional geometry in Ansys Mechanical. The cross section on the right shows the fault plane (highlighted in blue) and location of the cryobot void (red box).*

**References:** [1] Spohn, T., and Schubert, G. (2003) *Icarus, 161,* 456–467. [2] Greenberg, R., et al. (1998) *Icarus, 135,* 64–78. [3] Lee, S., Pappalardo, R. T., and Makris, N. C. (2005) *Icarus, 177,* 367–379. [4] Oleson, S., et al. (2019) NASA/TP–2019-220054. [5] Kargel, J. S., et al. (2000) *Icarus, 148,* 226–265. [6] Schenk, P. M., and Turtle, E. P. (2009) In: *Europa* U. Arizona Press, 181–198. [7] Wawrzynek, P. A., and Ingraffea, A. R. (1987) *Theoret. and App. Fract. Mech., 8,* 137–150. [8] Craft, K. L., et al. (2016) *Icarus, 274,* 297-313.