FURTHER DEVEOPMENTS ON SENDING SIGNALS THROUGH THE ICE (STI) ON OCEAN WORLDS

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Introduction: The ocean worlds Europa and Enceladus present some of the best potential habitats for life in our solar system. Traversing through the ice shell over several years and exploring the oceans or water pockets within would have many challenges. Here we present recent development progress by our ocean world STI team aiming to develop **robust fiber optic and free space communication radio frequency (RF) technology to enable successful science and exploration objectives at these exciting water worlds.**

Fiber optic tethers would face shearing challenges from potential fault motion in the ice shell [e.g. 1, 2] and chemical degradation, while the RF relays must remain thermally stable in extreme cold and high pressure environments, while transmitting under constrained power and form factor limits. RF and other forms of free space communication (optical, acoustic) would also be constrained by the composition and thermal conditions of the ice.

Approach: Recent developments by our STI team include: (1) modeling of ice shell thickness at Europa, (2) further characterization of the performance of optical tethers under Europa-like soak conditions (ice, ice + chemistries), (3) freeze-in tests, (4) pull-out ice adhesion tests and (5) thermo-mechanical design of an RF free space relay module [3-5].

Europa Ice Shell Thickness: Thermal and tidal models were used to run a conductive shell's temperature to equilibrium [3]. We find that shell thickness and surface heat flux are related and controlled by the amount of basal heat flux available at the ice-ocean interface. This is an unknown quantity for ocean worlds and, like the tide, may vary from location to location. With a constant basal heat, Q, from a well-mixed ocean for Q=1 mW/m^2 (lower internal heat) Europa's ice is found to be 35.5 km thick and release 19 mW/m^2 of heat at the surface or for Q=50 mW/m^2 (higher internal heat) the shell will be 10.5 km thick and release 55 mW/m^2. Further models are exploring variations due to surface temperature changes with latitude and effects of a convecting ice shell. Simulations for Enceladus conditions are also underway.

Optical Tethers: *Cold Soaks.* Long soak tests of tethers embedded in ice with/without impurities are being performed in an environmental chamber to investigate for potential performance degradation over time. Seven samples are being tested: two pure ice samples encasing Strong Tether Fiber Optic Cable (STFOC) and High Strength-STFOC (HS-STFOC) tethers (*Linden Photonics Inc.)*, and five with mixed chemistries in ice (NaCl, $MgSO_4$, Instant Ocean™ sea salt, H_2SO_4, and $FeSO_4$) encasing HS-STFOC tethers. Optical insertion losses were measured periodically using the methodology of [2] and results determined minimal signal loss thus far [4]. The tethers will undergo shear tests to characterize strength relative to controls at the end of their soak periods.

Pull-Out Behavior Tests. To quantify the jacket adhesion of current tethers in icy moon conditions, we are performing a series of pullout tests to assess the mechanism of strain distribution. Matrix (Ice) strength, directly proportional to temperature, fiber roughness and velocity are considered and tests will explore the full range of ice shell conditions at Europa. Experiments will test HS-STFOC and STFOC tethers, as well as samples of various potential jacket materials including certain polymers, as function of temperature at relatively warm deep shell (235-260 K) and cryogenic conditions (100-170 K). Velocities anticipated on creeping to active faults will be simulated [4]. **Figure 1** shows a custom insert for these tests, designed to manufacture cylindrical ice samples with tethers frozen inside, axially, and in tension. Pull-out tests will be performed in the LDEO cryogenic biaxial deformation apparatus with optical sensing.

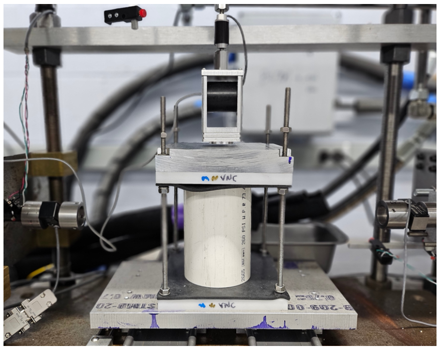

Figure 1. *Pull-out test apparatus at LDEO*

Freeze-in. During descent, an optical fiber would be payed out from the trailing edge of a melt probe and the melt water would refreeze around it, subjecting the fiber to the force induced by water-ice volume change, within the constrained pocket space, as well as the depth-dependent overburden of hydrostatic pressure. We are simulating this process with a custom test setup and testing tether performance and in-situ optical loss through fiber samples. To date, tests have been conducted on bare fiber at an overburden pressure of ±2100 psi, and future testing will include samples of STFOC and HS-STFOC.

RF relay. An RF communication architecture for a cryobot mission would consist of multiple relay modules housed at the back end of the cryobot that are periodically dropped off, and get frozen into, the melt-pocket behind. These modules then create a chain of relay modules that can pass a signal from the cryobot to the surface and vice versa. Building off our initial evaluation of a potential RF antenna design and performance for RF communication in a modeled Europa-like environment [6], we are working to consider thermal and mechanical constraints while maintaining a compact form factor so that multiple modules can fit inside the cryobot. This combination of constraints presents a nontrivial design challenge that had not previously been fully investigated.

Our design space is limited to communicating over the first 10 km of the ice shell as this portion is best suited for RF signals. This depth gives the bounding conditions of 3 ksi hydrostatic pressure (factor of safety (FOS) = 1.6) and 100 K ambient temperature. We chose to partially isolate the antenna from the primary structure by mounting the antennas externally rather than inside the primary structure. This simplified the primary structure design, made it more compact, and removed RF transparency as a requirement. However, this placed more demanding constraints on the antenna, requiring it to operate in the challenging ice shell conditions.

To date, have undergone 2 design iterations. **Figure 2** shows the current RF module design concept. This concept uses a graphite impact shell - radioisotope thermoelectric generator (GIS-RTG) which is an RPS utilizing half a GPHS and provides 125 Wth (beginning of life) and approximately 10 W electrical power [7]. This power source is based on a previously produced and used RPS from the Idaho National Laboratory, however it is not currently produced. The module utilizes a primary titanium pressure vessel to house the internal components with two externally mounted antennas in their own housings. The internal components consist of two electronics plates, harness, two batteries, the GIS-RTG and the thermal insulation. This configuration has an outer diameter of 37 cm, an overall height of 46 cm and a CBE mass of 73 kg.

The thermal design primarily utilizes partial vacuum within the pressure vessel along with Rohacell 31-HP (thermal conductivity of 0.035 W/mK at 300K). Thermal analyses of this design have been performed with a 100 K temperature applied to the outside of the module, a 125 Wth input applied at the GIS-RTG, and reduced convection conditions implemented inside to represent the partial vacuum. Results show the design provides adequate thermal control with internal components equilibrating at ~ 310 K (36 °C), well above minimum operation temperatures of -40°C.

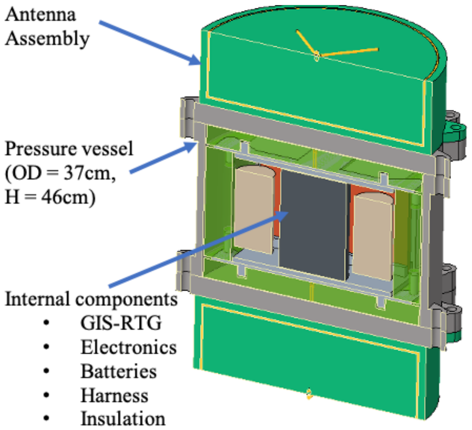

Figure 2. *Current thermo-mechanical RF relay design*

Structural analyses were also performed on the titanium structure: a 3 ksi hydrostatic load was emplaced to find the resulting Von Mises stress and verify that none exceeded 86 ksi (FOS=1.4). Results show only a few local contact points exceed the 86 ksi stress limit, indicating that our overall configuration and wall thickness are sufficient for the environmental load [5]. Further work is underway to address the remaining design challenges and produce prototypes for thermal and mechanical testing.

Summary: Many challenges exist for cryobot communication hardware within ocean worlds, including cryogenic temperatures, caustic chemistries, and tidal motions. Through our STI developments, we aim to address these and enable a future mission to explore the ocean of another world. Discovery awaits!

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