OCEAN WORLDS SIGNALS THROUGH THE ICE (STI) TECHNOLOGY – RETURNING DATA FROM DEEP BELOW.
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Introduction: Accessing the ocean or water pockets within an ice shell on an ocean world has challenges; a successful mission will need to penetrate the ice shell to distances of km to 10s of km, survive tidal stressing, potential faults, salts and other potentially corrosive chemistries, all while maintaining communication with the surface. **A robust communication strategy and hardware that can provide data transmission rates adequate to achieve science and exploration objectives are critical for any future missions to access an ocean world's subsurface.**

Previous studies of cryobot concepts have discussed the use of optical communication tethers with coupled radio frequency (RF) relay devices to enable communication between a descending probe and a surface lander (e.g. [1 - 4]). While tethers would face challenges of shearing in the ice shell and chemical degradation, the RF relays must remain thermally stable in extreme cold and high pressure environments, while transmitting under constrained power and form factor limits.

Approach: Work by our STI team over the last ~ three years on these communication technologies included: (1) characterization of the performance of optical tethers under Europa-like shearing conditions, (2) an RF antenna design fitting the form factor constraints modeled by previous studies for feasible cryobots, and (3) modeling of ice shell thickness and tidal stress inducing potential slip and strain on tethers crossing faults.

Tethers. The tethers tested included types previously used for ocean submersible exploration, Strong Tether Fiber Optic Cable (STFOC) and High Strength STFOC (*Linden Photonics, Inc.*). We embedded the tethers into pure water ice blocks and sheared them under applied force in a three-block double direct shear configuration [5]. Results showed the tethers continued to transmit data, with only low transmission reduction (<10 dB), at various stress levels and velocities, at temperatures ranging from 260K to 95K, and under vacuum. However, at the coldest temperatures minor damage to the outer tether jackets was observed.

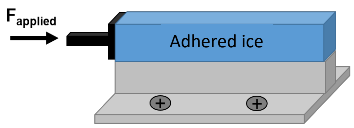
RF relay. Previously, we conducted an evaluation of a potential RF relay design and performance for RF communication in a modeled Europa-like environment. Considerations for the antenna design and operating wavelength included: maximizing gain in the vertical direction; minimizing gain dispersion over the chosen frequency range; balancing choice of operating frequency against background noise sources (galactic and planetary) and acceptable attenuation in ice (across expected temperature range, composition, and texture); and providing sufficient bandwidth to channelize communication by frequency while yielding sufficient data transmission rates. Additionally, the volume available for housing and deploying RF relay modules at Europa was based on constraints in current cryobot concept studies (e.g. [1,4]). These studies, however, restricted cryobot diameters in order to improve melt-through efficiency. Reliable operation of RF relays over an expected mission lifetime of several years though, requires attention to also be given to design optimization for thermal and structural challenges posed by ocean world ice shells, including temperatures that range from <80K to >200K, under large hydrostatic pressures, and in the presence of periodic (tidal) or rapid (fracturing) forcing.

Ice shell stress and fault modeling. Prior analytic and numerical modeling by the STI team has estimated the tidal stress with depth in Europa's ice shell, building off of [6], and constrained resulting potential fault slip strain hazards throughout a tidal cycle [7]. These models predict the thermal and deformational conditions that communication technologies will encounter at deployment and inform our tether and RF module designs and development tests to ensure survival and successful data transmission.

Current development efforts:

Tethers. Although the tethers have proven fairly resilient at cryogenic temperatures, improvements can be made and there are additional hazards including adhesion, shear geometry, and surrounding ice chemistry that require further tests and development.

Current developments include a new type of testing to account for a tether being pulled along length within ice (Figure 1), measuring its adhesion to ice, and design and tests with several candidate tether jacketing materials and strength layers (green and outer yellow layers, respectively, in Figure 2) focusing on improvements for Europa and Enceladus temperature, strain, and chemical conditions. Environmental chamber "soaks," embed tethers within ice of different compositions for months, measuring transmission performance over time, and upon removal evaluate any material degradation and characterize tether strength and transmission performance under shear.



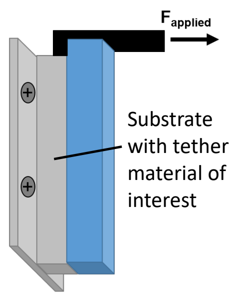


Figure 1. Ice Adhesion peel test, **(a)** tensile and **(b)** shear delamination modes, developed at CRREL to allow the study of various material classes and their adhesive properties with ice.

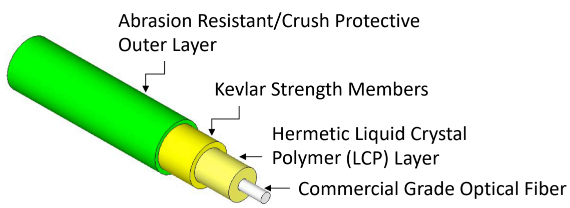


Figure 2. Layers of a *Linden Photonics Inc.* High Strength Strong Tether Fiber Optic Cable (HS-STFOC).

RF relay. An initial model was conceptualized to address the structural and thermal needs for a RF relay as a cylinder housing a core area of batteries, power/heating elements, electronics, and antennas. These central elements are surrounded by insulating foam (e.g., ROHACELL®) and encased in a 'roll-cage' outer structure (Figure 3). The overall size, structural design, amount and type of insulating materials, placement of internal components, and number of power/heating elements (i.e., RHU-RTG, RHU, and batteries) required to operate over a nominal mission lifetime is being evaluated through thermal and mechanical models and will be modified to produce prototypes for testing. The manufactured RF relay prototypes will undergo a set of thermal and mechanical tests at APL, using established facilities for materials characterization. A series of thermal balance tests as well as rapid and cyclic loading tests (to simulate fracturing events and tidal stress cycling, respectively) will be conducted over a range of temperatures representing deployment at multiple depths in an ocean world ice shell.

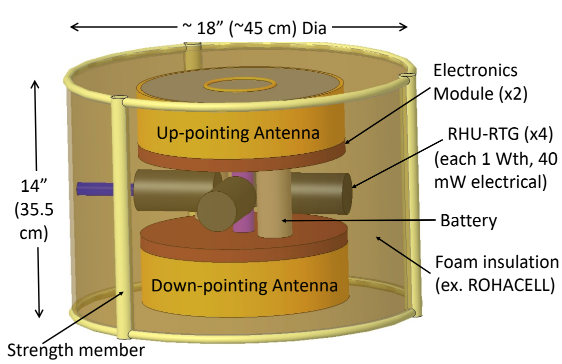


Figure 3. Notional design for a RF relay module concept that incorporates previous STI team antenna design work and considers thermal and mechanical needs for function in an ocean world ice shell.

Ice shell stress and fault modeling. Experimental data collected on the tethers and RF relay prototypes' test performances are compared to the numerical models developed to contextualize hardware tolerance and performance at Europa and Enceladus and identify where in the ice shells each technology is viable. Attention is given to specific environmental conditions and hazards identified including: Fault slip/motion induced by tidal deformation, causing strain on any device crossing through in the cold upper portion of the ice shell; Variation of thermal and pressure conditions from shallow to depth in the ice shell; Lateral variation of conditions on the ocean worlds, e.g. more heated polar regions vs. colder equatorial areas, max tidal bulging at sub-Jupiter or sub-Saturn locations vs. greater lateral forcing at other locations.

Summary: Development by the STI team of optical tethers and RF relay devices capable of providing communication to/from a cryobot as it tunnels its way through the ice shell at Europa and/or Enceladus, will enable the search for extraterrestrial life and exploration of oceans on other worlds. Communication hardware faces challenging technical risks due to the expected tectonic activity within the ice shells, their challenging thermal regimes, chemistries, and tidal motions. The STI work begins to address the fundamental thermo-mechanical challenges and needed design considerations for the hardware that are vital for a successful communication architecture.

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References: [1] Oleson et al. (2019) Europa Tunnelbot, *NASA/TP*—2019-220054. [2] Cwik et al. (2018) *69th International Astronautical Congress,* Bremen, Germany. [3] Bryant (2002) *IEEE Aerospace Conference, 1*. [4] Zimmerman et al. (2001) *IEEE Aerospace Conference, 1*. [5] Singh et al. (2021) *AGU* Fall Meeting, Abstract #859271. [6] Walker et al. (2020) *52nd LPSC*, Abstract #2448. [7] Lien et al. (2021) 53rd LPSC, Abstract #1005.