Ice-Embedded Tranceivers for Europa Cryobot Communications[1]

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Abstract—Several studies have been conducted to design robotic exploration vehicles for investigating a sub-surface water ocean within Jupiter's moon Europa. [1] [2] The current data from the Galileo spacecraft indicates a possible sub-surface ocean of undetermined depth covered by a water ice crust on the order of 10 kilometers thick. The ice crust also flexes several tens of meters every Europan day due to tidal forces. This presents several design challenges, especially for the communications link back to the science team on Earth.

This paper presents the modeling and analysis for a communications system using transceivers embedded within the ice crust. The work was done for a design study that examined using ice-embedded transceivers to communicate between a deep ice penetration "cryobot" at the liquid water ocean and a communications package on the Europan surface. [3]. This paper focuses on the microwave properties of ice and the communications link margin analysis.

TABLE OF CONTENTS

1. INTRODUCTION

The data from Voyager and Galileo space probes of the surface of the Jovian moon Europa indicate the possibility of a subsurface ocean. This has led to speculation on the potential for life existing below the surface in an environment powered by tidal heating of the moons interior.

The potential rewards of exploring that environment are matched by the difficulties and new challenges in reaching this potential ocean. A mission to explore Europa's ocean for evidence of life poses many unique problems. While NASA has visited the surfaces of several solar system bodies, it has never been faced with reaching the surface of a distant moon and then burrowing through kilometers of ice to reach the actual destination.

The Jet Propulsion Laboratory has conducted some design studies to examine the issues of Europa ocean exploration using a cryobot. The cryobot uses heat to melt its way through the crust instead of using a rotary mechanical drill. This method requires no moving parts while providing some steering and desirable ice-water sampling capability. [3]

Parts of these studies focused on the unusual communications problem posed by the interplanetary and inside-planet data relay. The design studies examined both tethered communications and radio-frequency transmission as possible solutions for the inter-crustal communications link. The studies assumed the ice will re-freeze behind the descending cryobot, a requirement for relaying at least 5 MB of data per day, a crust thickness of 10 kilometers, and certain mass and power constraints. Tethered communications were deemed to be high risk due to the tidal flexing. An armored tether that could withstand refreezing and tidal flexing was found to be too massive for transport to the Europan surface.

Radio-frequencies in water ice are attenuated much less than in liquid water. In the 30 GHz to 300 MHz region, the attenuation in ice is one thousand times less than the attenuation in liquid water. [4] A 100 MHz to 10 GHz radio-frequency communications link from the ocean to the surface was found to be physically possible, however the 10 kilometer distance required a prohibitive amount of power.

Instead, the design focused on independent tranceivers using patch antennas which were found to be effective from a data

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rate, mass, and risk assessment standpoint. The tranceivers would be deployed from the cryobot at specific depths and become embedded in the re-frozen ice crust. The design study calculated the link margin for different Europa crust temperature profiles and impurity assumptions.

The paper presents the link margin analysis along with the relevant radio frequency properties of water ice and the Europa crust models. The paper also discusses potential effects due to impurities.

2. EUROPA CRUST MODELS

Data from Voyager and Galileo space probes of the surface of the Jovian moon Europa indicate the possibility of a subsurface ocean. The surface of Europa is composed of entirely of water ice at approximately 100 degrees Kelvin. Evidence of volcanism caused by tidal heating in the neighboring moon Io led to speculation that the interior of Europa could be heated above the melting point of water. Surface features on Europa have been identified that provide evidence of cyclic surface bulging caused by the intense Jovian tidal force changes during each Europan orbit. This tidal bulging may be as large as 10's of meter at the surface.

This large tidal bulging appears to be responsible for the extensive fissure network at the surface. This type of environment would present a hazard even for armored tethers that are re-frozen into the crust.

Long-term studies of the data from the Galileo spacecraft reveal the potential for convective movement of the surface ice [5][6]. This has led to the development of two distinct models of the Europan crust.

Brittle lithosphere

Assuming the crust thermodynamics are dominated by conduction, a subsurface liquid water ocean would be covered by a brittle lithosphere several kilometers thick. The thermal profile should vary linearly with depth from 100 degrees Kelvin at the surface to 273 degrees Kelvin at the ice-water interface. For an assumed thermal gradient of ~50 degrees K/km, a brittle lithosphere could be as thin as 3.5 kilometers. However, this implies about 4 times the global, time-averaged heat flow predicted by steady state models. So an upper limit on a brittle lithosphere is probably closer to 10 kilometers thick.

Convecting sublayer

Recent studies have led some researchers to conclude that the Europan crust thermodynamics combine conduction and solid-state convection. The outer 1 to 2 kilometers of crust is a brittle lithosphere with a linear thermal profile from 100 degrees Kelvin at the surface to approximately 240 degrees Kelvin. Below 2 kilometers is a convecting sublayer extending to a depth of 5 to 20 kilometers at the ice-water interface. This convecting sublayer would have a roughly isothermal temperature profile between 240 and 260 degrees Kelvin, rising to 273 degrees Kelvin within the lowest 1 kilometer above the ocean.

These two models can both be addressed with the tranceiver communication systems, but require a different number of tranceiver units.

3. DIELECTRIC PROPERTIES OF WATER ICE

While liquid water appears clear at visible frequencies, it's nature as a good conductor makes it near opaque at microwave frequencies. However, in solid form, it's dielectric properties are very different in this range. From 1 - 100 GHz, the complex dielectric permittivity (or imaginary index of refraction) is about 1000 times lower for ice as it is for water [4] [7] as shown in figure 1. This feature enables radioglaciology and radio communications through ice.

Three major factors affect the permittivity: frequency, temperature, and water purity. The tradeoff in frequency was driven by the requirement for a small antenna but substantial data rates. The region around 1 to 10 GHz was found to be tractable for small patch antennas originally developed for MUSES-CN, the Mu Space Engineering Spacecraft –C Nanorover. The Nanorover was originally scheduled to fly with the MUSES-C spacecraft in 2002 as part of the first asteroid sample return mission. The nanorover part of the mission has been cancelled, but the work done on the patch antennas has proved to be valuable for other applications. The 1 to 10 GHz frequency range is near a minimum of the imaginary index of refraction for ice and would provide the maximum distance for a given power level. The penetration depth, p, defined as the distance through which the original plane wave is attenuated to 1/e of its original amplitude [8]:

$$p = \frac{\lambda_0}{4\pi \times n''} = \frac{\lambda_0 \sqrt{\varepsilon'}}{2\pi \times \varepsilon''} \tag{1}$$

This formula allows the data from figure 2 to be expressed as penetration depth in meters in figure 2. The dependency on wavelength in equation (1) means that for a given attenuation, lower frequencies penetrate farther into the ice. The figure also shows a variation with temperature, with the colder temperatures being significantly better.

Any estimate of the link margin in Europa crustal ice must consider the possibility of salt contaminants. Spectroscopy data from the Galileo spacecraft indicates hydrated materials that have been suggested to be salts. The presence of salt in water or ice has a large effect on the permittivity. In reference [9] the following equations were experimentally determined to govern the permittivity for pure ice and sea ice:

$$\varepsilon' = 3.1884 + 0.00091 \times T \quad (2)$$

And

$$\varepsilon'' = \frac{A}{f} + B \times f^{C} \quad (3)$$

Where T is temperature in degrees Celsius, f is frequency in GHz, and the parameters A, B, and C are listed in table 1. These numbers were determined from frozen sea ice and snow contaminated with NaCl impurities.

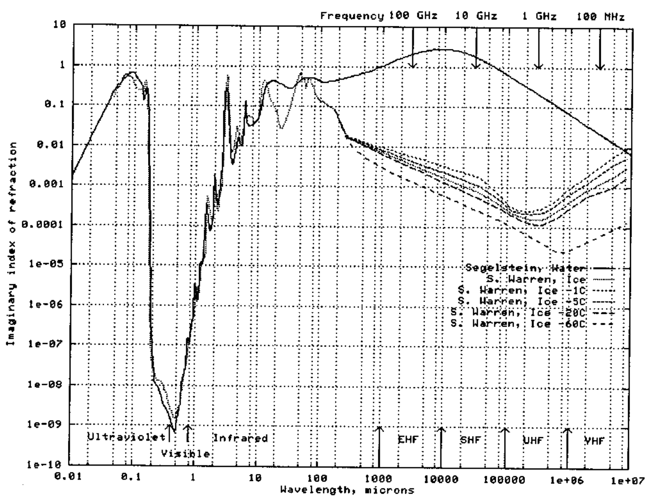

Figure 1 – Imaginary index of refraction for ice and water.

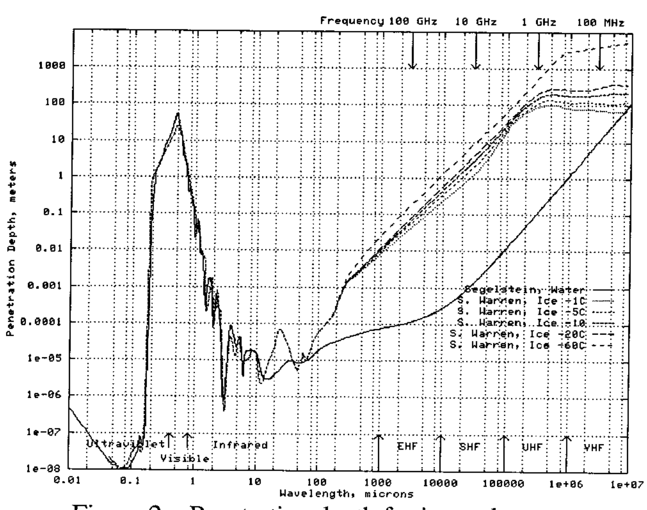

Figure 2 – Penetration depth for ice and water.

Table 1. Parameters in Ice dielectric formulas

Temp, C	NaCl, parts per million	A	B	C
-5	0	6.0e-4	6.5e-5	1.07
-5	13	2.6e-3	2.3e-4	0.87
-15	0	3.5^{e}-4	3.6^{e}-5	1.20
-15	13	1.3^{e}-3	1.2^{e}-4	1.0

For the region around 1 GHz, formula (3) was extended to cover other temperatures by extrapolating the quantity A+B to vary linearly with the log of temperature. This approximation was derived from reference [4] and led to the formulas for pure ice:

$$\varepsilon'' = 10^{-3.0129 + 0.0123 \times T} \quad (4)$$

and for 13 ppm NaCl:

$$\varepsilon'' = 10^{-2.398 + 0.0299 \times T} \quad (5)$$

Where T is temperature in degrees Celsius. These formulas were then used in the computation of the link margin analysis. The attenuation due to the media loss through ice is given by:

$$\frac{Power(z)}{Power(0)} = e^{-2z\frac{2\pi\varepsilon''}{\lambda\varepsilon'}} \quad (6)$$

Notice that the media loss results in power dropout with a scale of dB/km. Normal space loss has a dropout on a scale of dB/log(km). This fact makes the media loss dominate the link margin analysis.

4. TRANCEIVER DESIGN

An initial tranceiver design study focused on using 1 GHz patch antennas similar to those developed for the MUSES-C spacecraft. The design was constrained to fit into cylinders 10 cm in diameter and 2 to 3 cm tall. The top and bottom surfaces were covered with the patch antennas. The interior space contained memory storage, transmitter, receiver, and a radio-isotope heater unit power conversion module. A capacitor-based storage unit provided a means to increase power for burst transmissions. This provided the design goal of a 10 KHz data channel using 400 mW. For the design details, please see reference [3].

The tranceivers will provide the communications link between the lander base station on the surface and the decending cryobot. The base station will bury itself under a few meters of ice to protect the electronics from the Jovian radiation environment. Only an antenna will remain on the surface to complete the communications link back to Earth.

As the cryobot descends from the surface, tranceivers are deployed at the required intervals. The top tranceiver on the stack is pushed off the back of the cryobot into the liquid water melt space behind the vehicle. The tranceiver holds itself in place with a wire snare while the water re-freezes around it. The cryobot has the option of deploying the tranceivers at pre-assigned depths, or deploying them based on measured link margin performance between tranceivers.

5. Communication Link Margin

The media loss from the previous section must be multiplied by the space loss to the total transmission loss, Ls:

$$L_s = \left(\frac{c}{4\pi \times f \times z} \right)^2 \times e^{-2z\frac{2\pi\varepsilon''}{\lambda\varepsilon'}} \quad (7)$$

The link margin can then be specified in terms on the data channel signal to noise ratio. In this case, data are being transmitted from one tranceiver to the next tranceiver in the ice. Assuming that most of the transmitted power goes into the data channel, the ratio of signal to noise power is:

$$SNR = \frac{P_{TXR} \times \eta_{TXR} \times G_{TXR} \times L_s \times \eta_{RCV} \times G_{RCV}}{k \times T_{sys} \times f_d} \quad (8)$$

Where:
Ptxr = Power to the transmitter, assume 400 mW.
Ntxr = Transmitter efficiency, assume 25%.
Gtxr = Transmitter gain, 3.16 for 1 GHz patch antennas.
Ls = Total space loss, including media attenuation.
Nrcv = Receiver efficiency, assume 25%.
Gtxr = Receiver gain, 3.16 for 1 GHz patch antennas.
K = Boltzmann's constant, 1.38e-20.
Tsys = System noise temp for receiving antenna, 600 Kelvin for 1 GHz patch antennas.
Fd = data channel frequency bandwidth, nominally 10 KHz.

This equation does not factor in the substantial background noise temperature generated at 1 GHz by Jupiter. The assumption is that a cryobot mission would be deployed on the anti-Jovian face of the tidal-locked moon.

Equation (8) was solved using an iterative computer program starting at the ice-water interface and working upwards. At each location, the temperature was calculated from the assumed crustal profile (brittle lithosphere or conducting sublayer) and used to estimate the media loss. The program then iteratively solved for the maximum distance, z, that would support 10 KHz data channel with an SNR of 3 dB. Calculations were done for pure and salty ice.

Figures 3 and 4 show the number of tranceivers needed for a brittle lithosphere with pure ice and with salt impurities of 13 parts per million. The number of tranceivers varies from 4 for a 3.5 km pure crust to 14 for a 10 km salty crust. Figure 5 and 6 show the results for the convecting sublayer assumption with pure ice and with salt impurities. The smallest number of tranceivers needed is 8 for a 5 km pure crust. The number of tranceivers increases dramatically with depth and even more with the introduction of salinity.

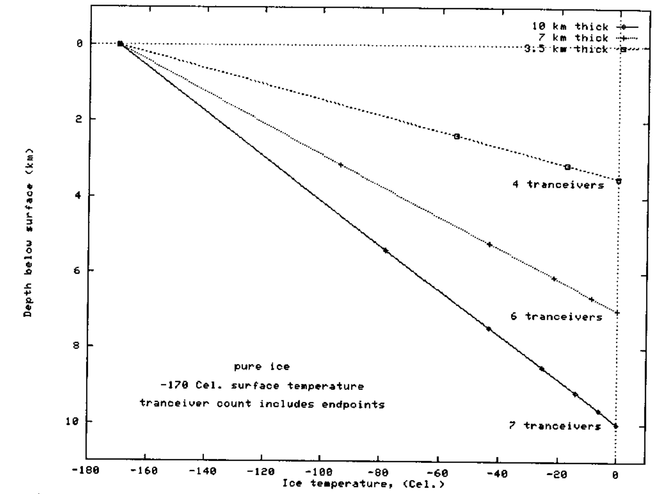

Figure 3 – Placement of tranceivers, pure brittle lithosphere

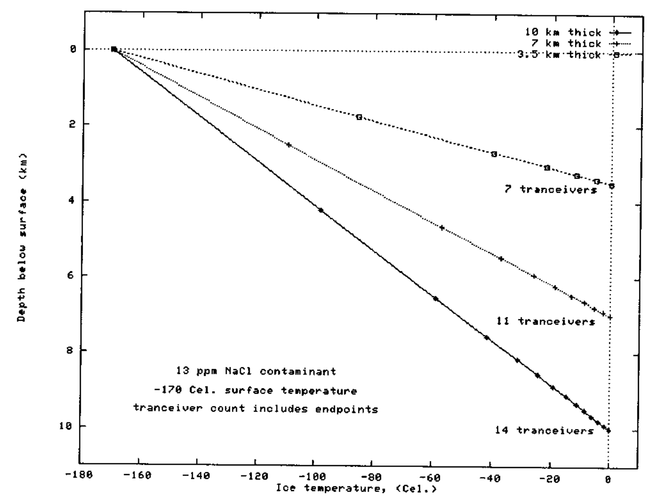

Figure 4 – Placement of tranceivers, salty brittle lithosphere

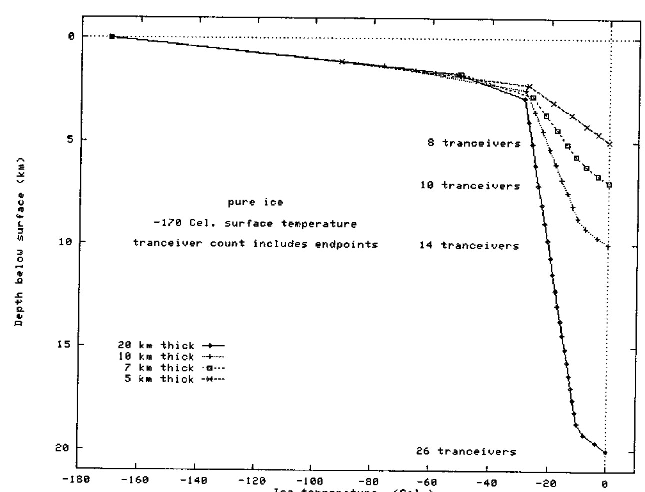

Figure 5 – Placement of tranceivers, pure convecting sublayer

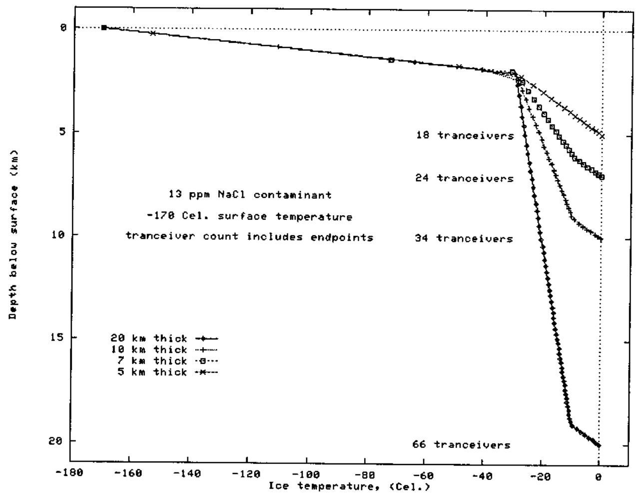

Figure 6 – Placement of tranceivers, salty convecting sublayer

6. CONCLUSIONS

A simplified link margin analysis supports the concept of using small tranceivers to send data through the ice crust of Europa. The number of tranceivers required is a strong function of the thermal model for the Europan crust. The number also increases when brine contaminants are introduced into the link margin analysis. If further study shows that the Europa crust has more than 15 parts per million salt contaminant, the number of tranceivers will become prohibitively large.

However, even the worst case can be solved using ice-embedded tranceivers. Given a fixed number of tranceivers, the actual data rate could be adjusted to meet the conditions of temperature profile and salinity.

For the conventing sublayer model, a combined tranceiver and tether approach may be possible. The tidal effects are greatest in the cold, rigid lithosphere, posing the largest risk to tether communications. However, this region provides the largest spacing between tranceivers due to the cold. Lower down, the ice becomes warmer, reducing the spacing between transceivers. However, this warm, ductile ice poses much less of a hazard to an embedded tether. Eventually a tradeoff can be made between the mass a tranceiver versus the mass of an length of tether equal to the tranceiver spacing. For the conditions described in this paper, the shortest spacing is about 100 meters.

The actual feasibility of the using transceivers will depend on making them compact enough to deliver and deploy between 7 and 14 of them. Improvements in power supplies and patch antenna gain will help reduce the number of tranceivers needed for the worst cases.

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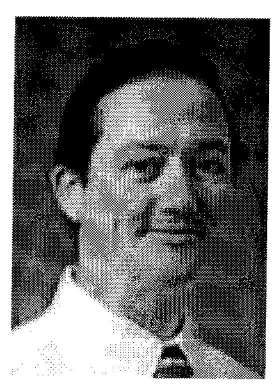

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principally involved with software design and development for spacecraft tracking, including holding the position of cognizant design engineer for the current DSN Sequential Ranging Assembly. He worked with the Europa Cryobot design team on the communications aspects, developing the model and performing the link margin analysis.