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Machine Learning for Characterizing Shallow Subsurface Ice via Radar-Thermal Data Fusion: Validation at Lake Vostok, East Antarctica

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Abstract

The forthcoming NASA Clipper and ESA JUICE missions to Jupiter's moon Europa will both carry a radar sounder and a thermal imager (REASON/E-THEMIS; RIME/MAJIS respectively). The synergy between the low resolution, volumetric sensitivity of sounding, and the high-resolution, surface sensitivity of thermal imaging, allows characterizing the upper meter that is accessible to landers and sample return missions. We combine machine learning and Bayesian statistics to develop a joint geophysical radar scattering and thermal model for ice. We validate the method by performing the joint inversion on remote sensing data of the ice sheet above Lake Vostok, East Antarctica. We discuss the applicability of the approach to Europa and quantify its performance in informing follow-up landing operations.

1. Introduction

Characterizing icy regolith properties via remote sensing will mitigate the risk of landed missions and maximize the scientific benefit of in situ exploration and sample return. Deep sounding by long wavelength radar is sensitive to dielectric constant, volume scattering and surface roughness, with a range resolution of tens of meters and lateral resolution of order hundreds of meters. Thermal imagers have much higher spatial resolution but only sense the outer centimeters. *So the upper 1-10 meters appears to be a 'blind zone' to remote sensing.* Still, thermal imaging does probe the outer meters, because temperature is a function of heat flow, ice sublimation, and ongoing geological activity, e.g. the presence of endogenic thermal anomalies and plumes. These in turn depend on subsurface structure, composition and ice shell thickness, which are characterizable through measurements of radar.

Property of the subsurface	Ice core value
Exponential densification factor	0.0021 m-1
Snow porosity	69%
Geothermal heat	0.05 W/m2
Charge-balance derived acidity	2 μM
Soluble chloride-ion concentration	2 μM

Table 1. Physical properties of the ice sheet above Lake Vostok from ice core data ([4,6]).

We do not have radar data of Europa yet. However, in preparation for the missions, we can study Europa's terrestrial analogs. Lake Vostok is a subglacial water body situated under about 4 km of ice in East Antarctica (e.g., [5]). Its ice sheet shows thermal and compositional radar horizons and structures that are similar to those expected on Jupiter's moon Europa [2]. Since several deep ice cores have been extracted from the ice sheet (Table 1), the study of the Vostok case provides ground truth for the validation of coupled temperature and radar backscattering modelling of ice. Here we demonstrate that a remote-sensing thermal and radar model (Fig. 1) may be inverted to retrieve the properties of the upper meter of the surface of ice sheet and the value of the endogenic heat at depth.

2. Methodology

Our approach is analogous to that used in [3] to constrain rock abundance on the surface of asteroids.

(1) We run 1125 simulations of coupled thermal-radar response of the ice sheet above Lake Vostok for different values of the following physical parameters: exponential densification factor of meteoric snow with depth (γ_s), surface porosity (c_s) of snow, geothermal heat flux at depth (Q), charge-balance derived acidity ($[H^+]$) and the soluble chloride-ion concentration ($[Cl^-]$). The ground truth values for

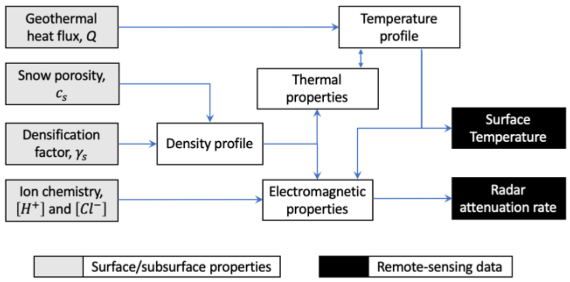

Fig. 1. Schematics of the coupled radar-thermal model.

these parameters are in Table 1. The thermal model is informed that the remotely-sensed surface temperature is equal to 218.15 ± 14 K (https://www.bas.ac.uk/). **(2)** Machine learning techniques allow generalizing the sparse look-up table of modeled radar-thermal simulations into a functional relationship. We use 70% the simulations to train a neural network able to associate the radar signal attenuation rate to the correspondent set of ice sheet properties. We use the rest of the simulations to validate and test the network. The error of the net in mimicking the "parent" model at testing is equal to $3\text{x}10^{-5}$ dB/km, with correlation index > 99%. **(3)** A neural network is a parametric function which can be statistically inverted (i.e., given an observed signal, we retrieve the best-fit set of ice properties). We employ the neural network as forward model in a Markov Chain Monte Carlo Bayesian inversion of the radar attenuation rate measured by [4]. Finally, we compare our estimate of the ice properties to the ice core data in order to validate the method.

The MCMC inversion of the remote sensing signal is successful and validates our approach, in the sense that the ground truth subsurface properties (Table 1) are among the range of solutions of the inverse problem (posterior distributions in Fig. 2). Assuming the mean values as the solution, the residual between the predicted and measured radar attenuation rates is below the noise level. The predicted temperature profile differs from the measured borehole temperature profile (not available from remote sensing) by 1 K on average.

3. Applicability

Our research is devoted specifically to maximize the scientific return of future missions to icy satellites (NASA Europa Clipper and ESA JUICE). This work will create an initial understanding of how thermal and radar imagers can be used together to significantly enhance remote surface characterization and inform follow-up landing operations. Our broader goal, however, is to develop a theoretical basis and practical implementation to simultaneous map the dielectric and thermal properties of regolith, which are physically connected. For this reason, this research is also applicable to other icy satellites (e.g., Enceladus), Mars, the Moon, and primitive bodies missions emphasizing radar and thermal imaging, e.g. CORE (COmet Radar Explorer, [1]). Future research will also include the use of radar surface reflectivity.

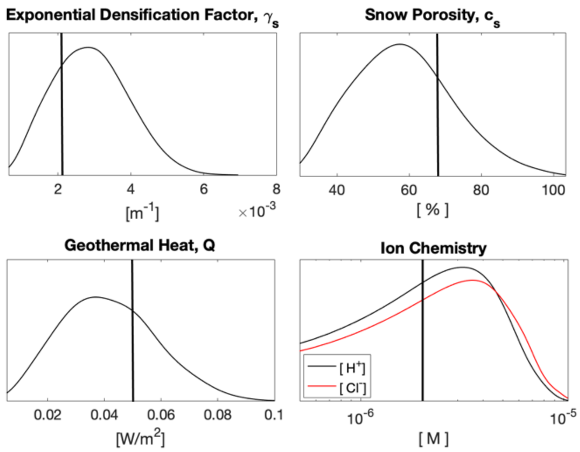

Figure 2. Normalized posterior distributions for the physical properties of the ice sheet. The vertical lines indicate the ground truth values in Table 1.

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