INTEGRATED SYNTHETIC APERTURE RADAR (SAR) AND MULTI-FREQUENCY GROUND PENETRATING RADAR (GPR) FOR SHALLOW ICE TARGETS IN TOMBSTONE TERRITORIAL PARK, YUKON, CANADA: INSIGHTS FOR THE INTERNATIONAL MARS ICE MAPPER MISSION (I-MIM)

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Introduction: Ground penetrating radar (GPR) is a geophysical technique that allows high-resolution and non-destructive stratigraphic imaging of the subsurface. The GPR method records the two-way travel time of electromagnetic (EM) waves reflected at boundaries between subsurface layers with contrasting relative permittivity [1]. Dielectric contrasts develop due to variations in sediment grain size, water content, and mineral composition. Synthetic aperture radar (SAR) is a side-looking active sensor, where the instrument transmits an electromagnetic pulse and then records the backscattered energy which varies due to wave interactions with the surface. SAR backscatter can provide information of the physical surface and subsurface characteristics (i.e. structure, surface roughness, moisture, etc.) [2].

The overall objective of this research is to correlate GPR-SAR surveys and datasets to determine the ideal frequency for imaging near-surface ice on Earth in preparation for the proposed International Mars Ice Mapper Mission (I-MIM) or a future orbiter radar payload on Mars. I-MIM aims to quantify the presence, depth to, distribution, and purity of water ice in reconnaissance zones that are favorable for future human exploration and colonization using an L-Band SAR system as its “anchor payload” [3]. In this study, we specifically want to identify and map near-surface ice and other structural features beneath the ground using GPR and SAR techniques to investigate the radar response in relevant ice-rich environments.

Study Sites: A field campaign was conducted in April 2023 at three study sites: (1) Two Moose Lake, (2) Chapman Lake, and (3) the Chapman Lake Airstrip. However, although all study sites have subsurface ice present, this study will focus primarily on Site 1: Two Moose Lake due to the density and spatial coverage of ice wedge high-center polygons with in-situ observations. Each site is located within the Tombstone Territorial Park in the Yukon Territory, Canada which is characterized by rugged mountain terrain and several permafrost landforms.

Methods: The GPR system used was the Sensors & Software PulseEKKO® system with antenna frequencies of 1000 MHz, 500 MHz, 250 MHz, and 200 MHz (Table 1). These GPR frequencies were “daisy-chained” to run all four frequencies simultaneously in a multi-channel array. The NIC (Network Interface Controller)-500X allows receivers to chronologically “listen” to their corresponding transmitter fire(s). For Site 1: Two Moose Lake, a common offset GPR survey grid (100 m x 30 m) was set up, while following the “zamboni” method making a zigzag pattern with survey lines spaced in 1 m intervals. 100 lines were oriented north-south and 30 lines were oriented in the west-east direction.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Time window</th>
<th>Approx. depth of penetration</th>
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<tbody>
<tr>
<td>200 MHz</td>
<td>100 ns</td>
<td>~10 m</td>
</tr>
<tr>
<td>250 MHz</td>
<td>~75 ns</td>
<td>5 m</td>
</tr>
<tr>
<td>500 MHz</td>
<td>50 ns</td>
<td>2.5 m</td>
</tr>
<tr>
<td>1000 MHz  (L-Band)</td>
<td>25 ns</td>
<td>1.25 m</td>
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</table>

Along with the common offset GPR procedure, we also use SARlab’s SlimSAR airborne instrument, which operates in the L-Band quad-pol, 1–2 GHz frequency (30–15 cm wavelengths) to acquire single look complex (SLC) data with a resolution of 0.7 m. SLC products are

Figure 1. GPR 2D radargrams showing four frequencies used for survey comparison. These radargrams are used to create depth/time slices and 3D geometry models of the ice-wedge.
images in the slant range by azimuth imaging plane, in the image plane of satellite data acquisition [4].

**Results:** Data collected from the GPR survey was interpreted via calculation of conductivity, permittivity, travel-time velocity, penetration depth, and radar reflection coefficient (RC) using the EKKO_Project software along with topographic data.

**Multi-frequency GPR Grid Scans:** Among the four frequencies used for the GPR surveys, the 500 and 250 MHz are the frequencies that best resolve ice wedge polygon subsurface geometry (Fig. 1). Ice-wedges measured typically have a length of 1.5-2.0 m. For the common offset method, the velocity was calibrated to be 0.162 m/ns, which is consistent with ice & frozen soil (0.13-0.16 m/ns) [6]. This value will be compared with another GPR survey (i.e. common midpoint; CMP), thus allowing for a more accurate velocity estimation.

**SAR Data Processing.** From the SLC data, a tri-polarization colour composite ($R = HH, G = HV, B = VV$) was created to show the various polarizations, which signify: $HH =$ like-polarized data used for the mapping of ice types (surface roughness), $VV =$ volumetric scattering, $HV =$ cross-polarized signals ($HV$ and $VH$) increase with surface roughness (Fig. 2B). Another way to determine the mechanism of scattering in radar images is through the calculation of the Pauli decomposition [5]. Fig. 2C shows the three RGB colours in a Pauli decomposition, which also represent the three dominant scattering mechanisms. This can also indicate the different polarization combinations of transmission and reception of the radar signal: $R = Double$-bounce scattering, $G = Volume$ scattering, and $B = Single$-bounce scattering. In both the colour composite and Pauli decomposition, the ice-wedge polygon region is dominated by double-bounce and volume scattering, indicative of snow or ice.

**Discussion & Future Work:** The total volume of ice will be calculated for both GPR and SAR methods. While there are complimentary datasets collected from various other surveys (NADIR L-Band radar sounding, LiDAR, electrical resistivity, etc.) it is important to integrate these carefully into one another.

**Correlation with sedimentology.** There are currently 9 sediment cores being prepared for sedimentological analysis (in summer 2024). The goal is to correlate stratigraphic facies associations between the GPR and cores to confirm grain size and dielectric properties.

**Circular polarization ratio (CPR).** CPR values >1 (typical of snow/ice) are good indicators of surface and subsurface roughness for buried ground ice on Earth [3-4]. We continue to explore hypotheses for CPR values and their significance for buried ground ice, which an L-Band SAR demonstrates the feasibility of by using this powerful technique of ice detection on Mars with I-MIM.

**Acknowledgments:** We would like to acknowledge all our collaborators listed, the Canadian Space Agency’s FAST grant awarded to IBS and the NSTP awarded to CNA which facilitated their fieldwork in the Yukon.


**Figure 2.** (A) Optical image of Site 1: Two Moose Lake in Tombstone Territorial Park using Maxar (Vivid) imagery with 1.2m resolution (left) and inset map (right) shows a GeoYukon aerial image with 0.15m resolution. (B) Tri-polarization colour composite with RGB colours signifying different polarizations: $R = HH, G = HV, B = VV$. (C) Pauli decomposition with RGB colours signifying different types of scattering mechanisms: $R = Double$-bounce scattering, $G = Volume$ scattering, and $B = Single$-bounce scattering.