Space Grant 2023 Summer Fellowship
Final Report

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Project Title: Development of UAS-Flown Ground Penetrating Radar Platform to Assess Spatiotemporal Variations of Soil Frost

Background:

Unpiloted Aircraft Systems (UAS) deployed for Ground-Penetrating Radar (GPR) applications hold significant promise for assessing numerous frozen ground and freeze-thaw processes. Integrating a UAS-flown platform with GPR capacity offers a novel approach to characterizing snowpack properties and freeze-thaw dynamics in challenging environments. By combining the mobility and enhanced spatial range of a UAS platform with the subsurface imaging capabilities of GPR, spatially continuous measurements of snowpacks and the frozen subsurface can be acquired without the need to disturb the snowpack. Researchers can utilize UAS-flown GPR to extract ultra-high-resolution subsurface reflective imagery and radiograms of properties such as snowpack depth, snow water equivalent (SWE), and soil frost depth. This capability enables comprehensive assessments of snowpack density, depth, and structure, contributing to a deeper understanding of snow accumulation and ablation patterns or seasonal soil frost spatiotemporally varies. UAS-flown GPR presents further practical advancements as UAS-flown surveys of snowpack do not directly disturb the snowpack structure, thereby allowing more authentic, undisturbed measurements.

However, deploying UAS-flown GPR for snow and frozen ground studies does pose several unique engineering and regulatory challenges. The most pertinent barrier to UAS-flown GPR surveys is the Federal Communications Commission regulation that all airborne GPR must only be active from 1 metre above the surface and below. Effectively, this necessitates that UAS-flown GPR remains close to the surface requiring precise flight planning piloting of the UAS platform. Additionally, due to the weight of the GPR antenna and controller payload, pilots must also consider the weight of the UAS platform and decreased flight times and navigation performance. Designing a UAS platform that can include these challenges while still carrying a GPR equipment payload is crucial for reliable data collection. Moreover, interpreting GPR data detailing snow and soil frost conditions presents unique complexities. Distinguishing the snow-ground interface and the precise soil frost depth within radiograms can be complex. However, this emerging research seeks to engineer an approach allowing remote sensing scientists to construct efficient flight plans and high-quality soil frost and snowpack depth datasets.

Research Goals:

1. Develop and Test a UAS-flown GPR platform that is capable of detecting frozen soil conditions and snowpack depth.
2. Design flight plans for UAS-flown GPR that will capture the small-scale spatiotemporal variability of soil frost and snowpack properties.
3. Develop a protocol for processing UAS-flown GPR radiograms to extract snowpack and soil frost depth.

Research Questions:

1. How can we engineer a UAS-flown GPR platform to observe snowpack and frozen ground properties?
2. How can UAS-flown GPR be flown in an efficient manner to capture the spatiotemporal variation in snowpack and soil frost depths, while meeting FCC regulations?

3. What type of UAS flight plan is the most spatially and temporally efficient to capture spatiotemporal variability of snowpack and soil frost properties?
4. How can we detect differences in soil frost depth across space and time using UAS-flown GPR measurements?

Description of Research Activities:

All research and testing were conducted at either the Thompson Farm Research Observatory outside of Durham, NH, USA or at a privately-owned pasture plot loaned to UAS-GPR research pursuits outside Newmarket, NH, USA.

The first step in developing a UAS-flown GPR platform was the attachment of the GSSI 900Hz GPR antenna and GSSI SIR4000 GPR controller unit to the DJI Matrice600 UAS platform. A 900Hz unit was previously selected as the best frequency antenna to detect snow and soil frost properties based on known depths of soil frost and snow at the Thompson Farm property. The 900Hz GPR antenna allows for up to 2m penetration into the subsurface. Considering the constraint that approximately 1m of that possible range will consist of the air gap between the UAS and the ground surface, the effective penetration depth was a maximum of 1m. Hoheneder et al. (forthcoming) determined that soil frost in the Thompson Farm open pasture reaches a maximum seasonal depth of approximately 35cm, including the 1m maximum. To attach the GPR antenna and controller unit to the UAs platform, a metal chassis was custom developed to hold both units (**Figure 1**). This chassis places the antenna at the bottom of the UAS platform, where no obstructions would interfere with data collection. To test the stability of the platform several non-designed flights were conducted to test the stability and performance of the platform. Testing revealed that the UAS maintained a maximum flight time of approximately 10 minutes with the payload.

Figure 1: UAS-GPR Platform Consisting of a GSSI 900Hz Ground Penetrating Radar Antenna, GSSI SIR 4000 Controller Unit mounted on a DJI Matrice 600 UAS

After the GPR unit and controller were attached, additional components were integrated within the UAS platform to improve the quality of data collection and flight performance. A GEODE Multi-GNSS GPS unit was affixed to the UAS platform and the SIR4000 controller unit to extract the location of GPR measurements and precise flight locations. Additionally, a radio switch and connection were installed on the DJI M600 controller that interfaced with the SIR4000 controller allowing for survey transect marks to be placed while the UAS platform was in flight. Each time the user moved the radio switch downward, a survey transect mark would be placed in the active radiogram.

Finally, a UAS-purposed radar altimeter (24Ghz Nanoradar NRA24) and laser altimeter (Lightware SF30/D) terrain following module from SPH Engineering was installed on a flight arm of the UAS platform. This improvement was deemed necessary after initial near-ground testing proved difficult with the payload and FCC flight regulations. Previously, altitude was calculated using an onboard altimeter within the UAS platform. Given the fine flight margins of not colliding with the surface and the GPR antenna remaining FCC compliant, terrain following was theorized to improve the safety and consistency of piloting the UAS. Additionally, terrain following was theorized to improve the stability of the air gap to ground interface, allowing for more streamlined radiogram processing. The terrain following module was tested by flying single-line flight and observing the steadiness of the UAS platform. The module performed well in clear, cut-grass areas. However, in unkept or naturally covered regions, there was less rigidity in the terrain following, which caused the UAS platform to shift upwards. The vertical movement of the UAS platform is likely a result of the terrain following module recognizing an obstacle and correcting its altitude. However, in an ultimate sense, this approach was observed as a significant improvement compared to the onboard altimeter.

Flight planning was conducted by using DJI flight planning software. A double-grid flight pattern was theorized to be the most effective for capturing the three-dimensional (3D) spatial variation of snow and soil frost properties. This flight plan includes a grid in a North-South aspect, followed by a second grid of flight lines in an East-West, perpendicular orientation. Row spacing was conducted at 50cm between each flight line as recommended by the methodology of Butnor et al. (2014). In this study, ground-coupled soil frost measurements were retrieved using a row spacing of roughly twice the width of the GPR antenna. This same approach was applied to this research; however, given the nature of UAS-flown GPR, increasing the row spacing, a greater field of viewership is likely applicable but went untested. Four solid, 1m-long aluminum rods were placed across a pasture in the Newmarket property to extract specific target depths. Two rods were buried at an approximate depth of 10cm, and a third was buried at 25cm to simulate the depth of typical seasonal soil frost. The fourth tube was deployed as a surface reference and kept on the ground, unburied. Flight plans were designed to be concurrent with the locations of these aluminum rods so that flight lines passed overtop of all four rods in both orientations. Two flights were conducted to extract testing data. As soil moisture can interfere with the quality of results, flights were only conducted when the soil was theorized to be primarily dry and free from any residual moisture or dampness.

Radiogram processing was conducted using the GSSI RADAN 7 software. Processing recommendations stemmed from workshops with GSSI employees and GPR technicians and the software processing recommendations. Specific processing steps included an IIR Filter, an Adaptive Gain algorithm, Deconvolution Filter, and Surface Normalization. Processed radiograms were produced for each testing flight (**Figure 2**). As GPS coordinates of flight lines and survey transect marks were collected across both testing flights, it was possible to export these data into useful spatial data formats. Based upon initial returns, the ability to visually identify and extract the depth of each of the four reference aluminum tubes appears possible. As a corollary, this also proves that extracting other spatially-oriented properties, such as snow depth and soil frost depth, will be possible.

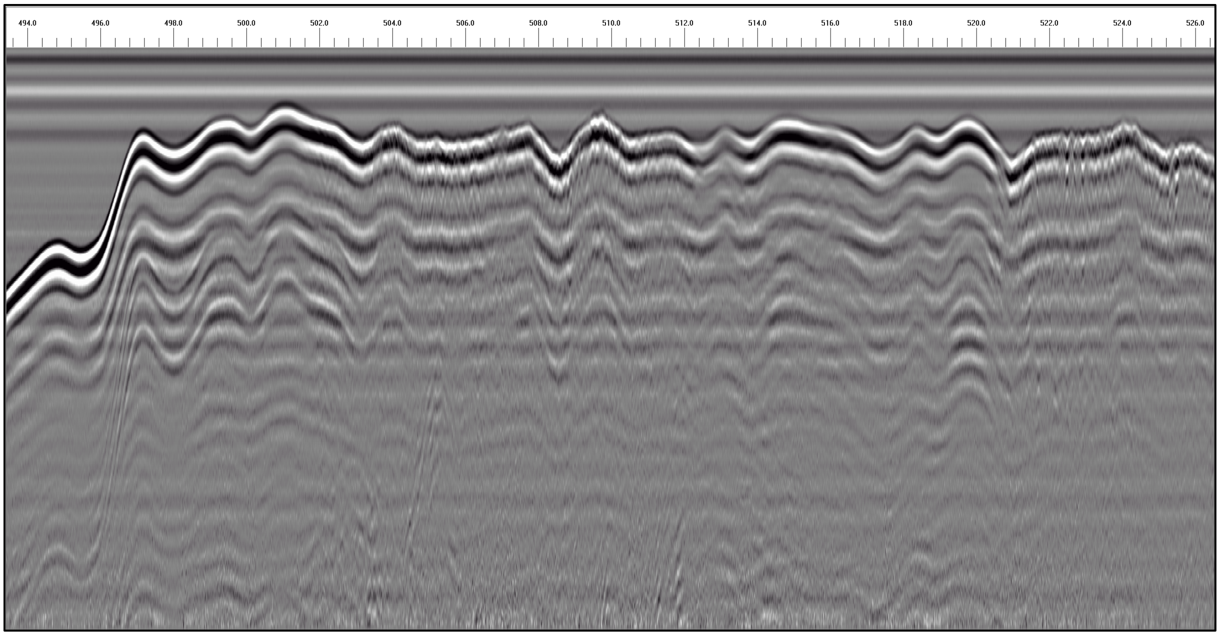

Figure 2: Processed radiogram sample from the Newmarket Property on an August 13th, 2023 test flight. Aluminum tube sites are present in the center and far-right of the radiogram.

Future Works:

The research activities outlined in this report occurred throughout Summer 2023. No naturally frozen ground or snowpacks were observed within this time period. The lead researchers acknowledge that the goal of the above work was to establish proper design and capacity for the UAS-flown GPR platform and to test the rigour and potential for intended winter protocols. Thus, the work conducted during Summer 2023 will continue into the 2023-2024 winter field season.

Tentatively, to test the capacity of UAS-flown GPR to detect snow and soil frost depth, two transects at the Kingman Research Farm property in Madbury, New Hampshire, USA, will be established. The first transect will be located in the Kingman Farm open pasture land cover. These open pasture transects will be a 2D to 3D spiral pattern, as McGrath et al. (2022) first demonstrated in collecting snowpack depths. The spiral pattern represents an improvement over the 3D double grid flight pattern as this pattern does not require the deletion of data when the UAS is turning or moving to the following flight line. The same spatial extent can be captured, but all data within the area is considered valuable instead of only a selection of the data. This approach is theorized to improve flight efficiency and conversions from 2D radiograms to 3D spatial data. A second plot will be established within the Kingman Farm Forest land cover. This second transect will exclusively consist of 2D, single-line transects.

The ultimate goal in collecting data from two different land cover classes is to assess how soil frost and snowpack spatiotemporally vary and how land cover influences their development and any freeze-thaw cycling. Furthermore, there need to be more UAS studies that occur in forested areas, an even more significant paucity of UAS-derived snow depth studies in forested areas, and the deployment of UAS-flown GPR in a forested setting is theorized to be the first of These data will help to bridge the gap between situ and satellite-derived data products and improve the accuracy of models. Additionally, as the deployment of UAS-flown GPR is an entirely novel approach, the study's results will provide one of the first glimpses into how snow and frozen ground data can be collected in a forest setting, thus further improving modelling approaches.

Works Cited:

Butnor, J. R., Campbell, J. L., Shanley, J. B., & Zarnoch, S. J. (2014). Measuring soil frost depth in forest ecosystems with ground penetrating radar. *Agricultural and Forest Meteorology*, *192*, 121-131.

McGrath, D., Bonnell, R., Zeller, L., Olsen-Mikitowicz, A., Bump, E., Webb, R., & Marshall, H. P. (2022). A time series of snow density and snow water equivalent observations derived from the integration of GPR and UAV SFM Observations. *Frontiers in Remote Sensing*, *3*, 886747.