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Abstract— **Radar survey of the Antarctic shear zone was conducted using an ultra-wideband (2-10 GHz) frequency modulated continuous wave (FMCW) radar. The radar was mounted on a sled and pulled by a robot that was specifically designed to operate in a harsh polar environment. Our FMCW radar had good penetration through Antarctic snow and we observed snow stratigraphy to a depth of 20 m. The radar images also revealed multiple crevasses in the shear zone. Our results demonstrate that autonomous survey using high frequency radar is feasible and safe approach for detecting hidden crevasses.**

Keywords- Crevasse, FMCW radar, robot, Antarctica

I. INTRODUCTION

A tractor convoy towing sleds is a cost-effective method for transporting material and fuel across the Antarctic continent. To service the South Pole Station, this convoy must traverse a crevasse field that separates the McMurdo and Ross Ice Shelves. Crevasses that form in this shear zone are completely covered by snow accumulation and high wind, and therefore present no surface expressions. To ensure safe navigation across this shear zone it is necessary to detect and mitigate these crevasse hazards. The location and breath of each crevasse and the thicknesses of the overlying snow bridges are critical data needed to assess the crossing. A 400 MHz ground penetrating radar (GPR) is a proven technology for crevasse detection [1, 2] and is currently being used by the U.S. Antarctic Program (USAP) in the shear zone. The standard crevasse-detection method is to push a GPR antenna in front of a tracked vehicle with an operator inside to read the radar screen. Upon crevasse detection, the vehicle must be able to stop within 2 seconds to avoid crossing a thin snow bridge. This puts the radar operator and vehicle driver under considerable strain and some risk. New techniques that can improve and/or complement the existing GPR method for crevasse detection are needed.

Robots are widely used to carry out dangerous tasks in place of humans. We used a robot to demonstrate a safe procedure for detecting crevasse hazards in support of Antarctic logistics. A robot (named *Yeti*) designed to operate in harsh polar environment [3] was used to obtain radar reflection profiles in the shear zone. Ultra-wideband (2-10 GHz) frequency modulated continuous wave (FMCW) radar mounted on a sled was pulled by *Yeti*. We used the high frequency radar to take advantage of the smaller antenna footprint and larger antenna bandwidth (compared to the 400 MHZ GPR currently in use). This greatly improved both the spatial and temporal resolutions of the crevasse features. The high frequency FMCW radar detected snow stratigraphy and crevasses to depth of 20 m in the Antarctic shear zone. Our preliminary results demonstrate that a safe navigation over a crevasse field can be achieved by exploiting robot/radar autonomous survey.

II. EXPERIMENT

A. FMCW radar

Various radar waveforms (impulse, step-frequency, FMCW) have been used to investigate snow pack properties. For example, commercially available impulse radars are currently used operationally in Scandinavia's deep snow packs [4, 5]. Impulse radars have also been used for snow pack studies on glaciers [6]. High-frequency FMCW radars are widely used for seasonal snow cover studies [7]. One advantage of the FMCW radar waveform is the wide bandwidth that can be achieved at a moderate cost. The wide bandwidth improves the vertical resolution of the radar. Therefore, FMCW radars are well suited for measuring shallow snow depths and detailed snow stratigraphy.

FMCW radars are also good candidates for crevasse detection. The high frequency radar can be used to take

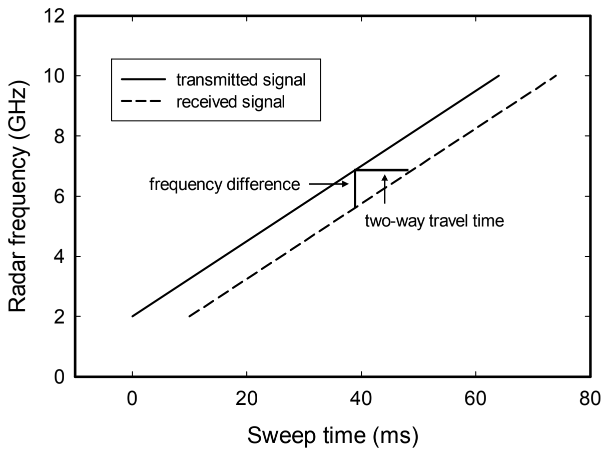

Figure 1. Frequency vs time relationship for a 2-10 GHz FMCW transmitted (solid line) and received (dashed line) waveforms.

Figure 2. 2-10 GHz FMCW radar developed for alpine snow cover studies. This radar was used for crevasse detection.

advantage of the spatial and temporal resolution that cannot be achieved using the low frequency 400 MHz GPR. This improved resolution comes at the expense of signal penetration into ice. However, crevasses are near surface targets located in an ice medium that has low loss factor at microwave frequencies. Therefore, the decrease in radar penetration may not be a significant factor.

The salient feature of an FMCW radar is that it measures the distance to a target (i.e. snow layers, snow-air interface) from the instantaneous frequency difference between the transmitted signal and the received signal. The equation governing the operation of an FMCW radar is

$$F_d = \frac{2BW d\sqrt{\varepsilon}}{cT_s}$$

where F_d is the frequency difference, d is the distance to a target, T_s is the sweep time of the modulated signal, BW is the radar bandwidth and ε is the relative permittivity of the medium. The instantaneous frequency difference between the transmitted and received signal is proportional to the two-way travel time of the received signal. This frequency difference is obtained by mixing the transmitted and received signal and by performing a fast Fourier transformation on the mixer output. Therefore, the output of an FMCW radar is a power spectrum where the frequency differences represent various targets (electromagnetic discontinuities) encountered by the radar signal. Figure 1 illustrates the relationship between sweep time and frequency of the FMCW radar used in our investigation. T_s and BW of the radar system are 64 ms and 8 GHz, respectively.

We selected a 2-10 GHz FMCW radar for crevasse detection. This radar was built and optimized for operation in shallow seasonal snow cover. The radar is field portable and can be easily adapted to operate on any platform (i.e. helicopter, sled, and tripod). Figure 2 illustrates the radar being pulled by two skiers in alpine snow. The frequency sweep of the radar is produced using (Yttrium Iron Garnett (YIG) oscillator. Broadband (1-18 GHz) double-ridged antennas provide additional frequency agility. This radar produced excellent results in numerous field tests. We tested this radar for crevasse detection without any modification. The radar parameters that were previously optimized for the snow cover studies were used. This study is the initial effort to identify the optimum radar parameters for crevasse detection using high frequency FMCW radars.

B. Robot

The robot, *Yeti,* is a 71-kg, four-wheel-drive, battery-powered rover specifically designed to tow ground-penetrating radar to detect crevasses in Antarctic and Greenland ice sheets. It can be operated manually via radio control or pre-programmed to follow GPS waypoints to execute a survey grid. The high-mobility chassis has a central pivot to allow four-wheel ground contact over rough snow. The onboard GPR radar control unit (GSSI SIR 3000) operates

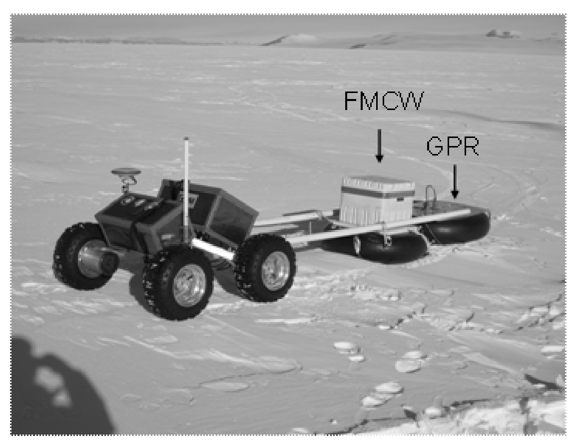

Figure 3. *Yeti* pulling a 2-10 GHz FMCW radar and a 400 MHz GPR antenna.

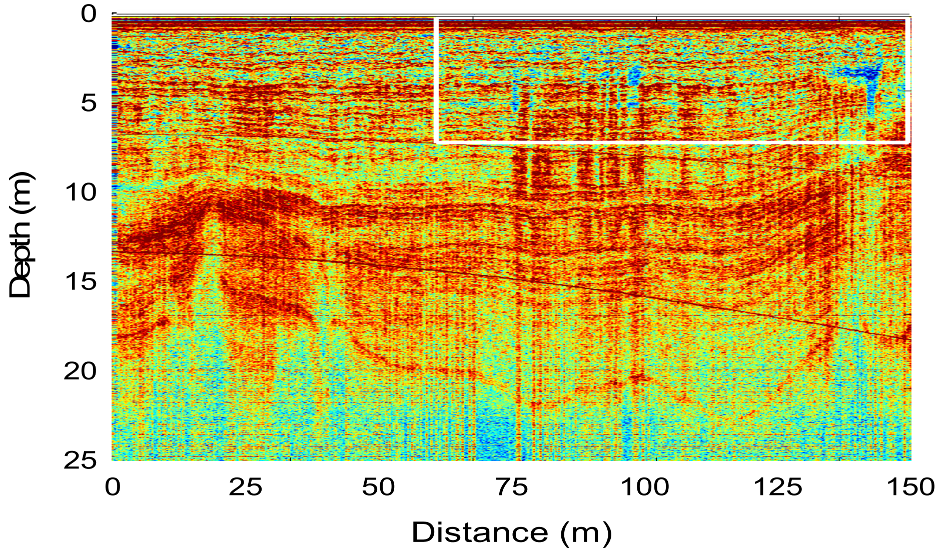

Figure 4. Shear zone radar reflection profile obtained using 2-10 GHz FMCW radar.

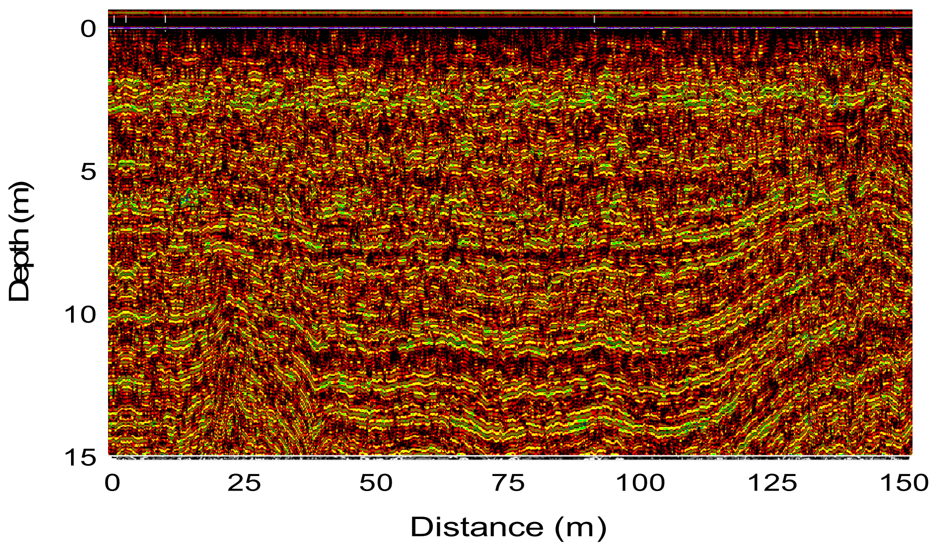

Figure 5. Shear zone radar reflection profile obtained using 400 MHz GPR.

continuously and records data for subsequent review by skilled operators. A 400 MHz antenna is suspended in an inflated tube and pulled by *Yeti*. For this investigation, we co-located the FMCW radar on a second tube. The radar and the data acquisition system were inside an enclosure that rested on the inflated tube. Figure 3 illustrates FMCW radar and 400 MHz antenna being pulled by *Yeti*. The co-located radars allowed us to compare radar reflection profiles from two systems with different waveforms and wavelengths.

We deployed *Yeti* across the shear zone on two days in October 2009 concurrent with human-operated radars. It conducted initial surveys across a known crevasse and then completed continuous outbound and inbound surveys across the entire 5 km shear zone. The surveys were conducted at steady speeds of either 3.2 or 6.4 km/hr. Air temperatures were about -30C and *Yeti* weathered two overnight snowstorms with no adverse effects.

III. Results

Radar reflection profiles obtained using high-frequency FMCW radar and low-frequency impulse GPR are presented. The FMCW radar profile collected at the shear zone is illustrated in Figure 4. The red and blue colors represent strong and weak reflected signals, respectively. The profile distance of 150 m was estimated from the known sweep time of the radar waveform and *Yeti's* speed of 3.2 km/hr. The profile depth was estimated using snow density of 0.5 g/cm^3 which corresponds to relative permittivity $\varepsilon = 2.0$ [8]. Several important shear zone features are present in this profile. Most

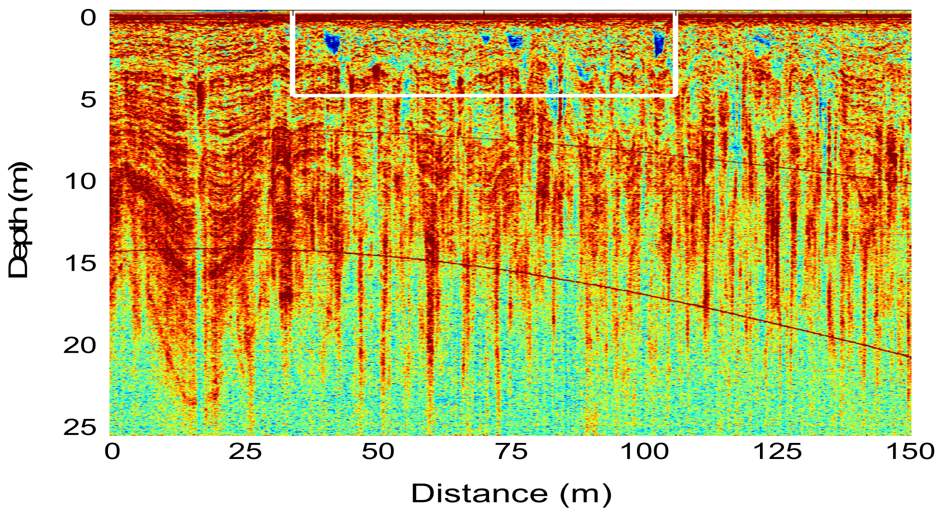

Figure 6. Shear zone radar reflection profile obtained using 2-10 GHz FMCW radar.

notable is the crevasse located 20 m from the start of the profile. The depth of the crevasse is 10 m. The snow stratigraphy around the crevasse comes to an abrupt end at one side and then resumes on the opposite side. As we move further along the profile (25m to 150m), the radar reflections indicate a crevasse free zone where the snow layers are continuous. Several pockets of low radar reflections are present (these are the blue areas within the white rectangular box). Since the FMCW radar operates at high microwave frequencies, the reflections from these layers and pockets are likely due to changes in snow density and/or snow texture.

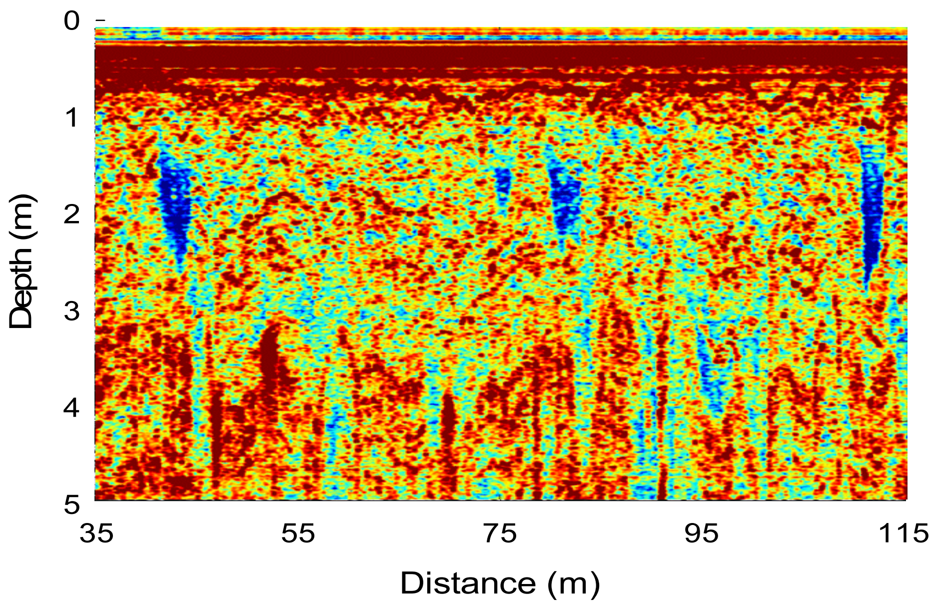

Figure 7. Expanded image (area highlighted by a rectangular box in Figure 6) of radar reflection profile obtained using 2-10 GHz FMCW radar. Voids or pockets of low density snow occur at 2 m depth.

Figure 5 shows the shear zone profile obtained with a 400 MHz GPR. The GPR was located next to the FMCW radar so we could compare the results from the two radars. The time range setting of the GPR for these measurements limited the profile depth to approximately 15 m. Comparison of Figures 4 and 5 shows that two radars detected the same subsurface features in the shear zone. However, due to the smaller wavelength, smaller radar footprint and wider radar bandwidth, the FMCW radar resolved these features better than the 400 MHz GPR. The penetration of the FMCW radar wavelengths into the shear zone allows us to detect layers to a depth of 20 m. Since the signal penetration in the shear zone does not appear to be an issue, we believe that high frequency

FMCW radar can be used to detect crevasses in the Antarctic shear zone.

Figure 6 shows another FMCW radar reflection profile collected from the shear zone. The figure shows a crevasse around 20 m into the profile. However, unlike Figure 4, the snow layers at this location are not continuous. The discontinuities in the layering indicate that the snow processes at this location are more dynamic than those illustrated in Figure 4. These discontinuities are caused by small crevasse-like features. These features are illustrated in Figure 7, which is an expanded view of the radar profile highlighted by a white box in Figure 6. Three features characterized by low radar returns (blue areas) are present at 2 m depth. They occur at profile distances of 40 m, 80 m and 100 m. We interpret these areas as voids or pockets of low density snow. We do not have a reasonable explanation for the processes responsible for these small crevasse-like features.

IV. Summary

High frequency, ultra-wideband (2-10 GHz) FMCW radar reflection profiles were collected in the Antarctic shear zone. Crevasses and snow layering in the shear zone were detected to a depth of 20 m. These results were obtained using a robot pulled radar to demonstrate that a safe procedure for detection of crevasses is possible using an autonomous radar survey.

Acknowledgment

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