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Laura Ray, Madeleine Jordan, Steven A. Arcone, and Benjamin Walker

*Dartmouth College
Thayer School of Engineering
Hanover, NH 03755*

Lynn M. Kaluziński, Peter Ortquist Koons, and Gordon Hamilton

*University of Maine
School of Earth and Climate Science
Orono, ME 04469*

James H. Lever

*Cold Regions Research and Engineering Laboratory
U.S. Army Engineer Research and Development Center
72 Lyme Road
Hanover, NH 03755*

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Preface

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Velocity field in the McMurdo shear zone from annual ground penetrating radar imaging and crevasse matching

ABSTRACT

The McMurdo shear zone (MSZ) is a strip of heavily crevassed ice oriented in the south-north direction and moving northward. Previous airborne surveys revealed a chaotic crevasse structure superimposed on a set of expected crevasse orientations at 45 degrees to the south-north flow (due to shear stress mechanisms). The dynamics that produced this chaotic structure are poorly understood. Our purpose is to present our field methodology and provide field data that will enable validation of models of the MSZ evolution, and here, we present a method for deriving a local velocity field from ground penetrating radar (GPR) data towards that end. Maps of near-surface crevasses were derived from two annual GPR surveys of a 28 km² region of the MSZ using Eulerian sampling. Our robot-towed and GPS navigated GPR enabled a dense survey grid, with transects of the shear zone at 50 m spacing. Each survey comprised multiple crossings of long (> 1 km) crevasses that appear in echelon on the western and eastern boundaries of the shear zone, as well as two or more crossings of shorter crevasses in the more chaotic zone between the western and eastern boundaries. From these maps, we derived a local velocity field based on the year-to-year movement of the same crevasses. Our velocity field varies significantly from fields previously established using remote sensing and provides more detail than one concurrently derived from a 29-station GPS network. Rather than a simple velocity gradient expected for crevasses oriented approximately 45 degrees to flow direction, we find constant velocity contours oriented diagonally across the shear zone with a wavy fine structure. Although our survey is based on near-surface crevasses, similar crevassing found in marine ice at 160 m depth leads us to conclude that this surface velocity field may hold through the body of meteoric and marine ice. Our success with robot-towed GPR with GPS navigation suggests we may greatly increase our survey areas.

1. Introduction

Ice shelves are floating sheets of ice that form when a glacier flows from land onto the ocean surface. Ice shelves act as a buttress to ice sheets and glaciers and thus their collapse can cause ice on land to accelerate the flow rate into the ocean. On the Ross Ice Shelf, the largest ice shelf in Antarctica, an important region of lateral resistance is the McMurdo Shear Zone (MSZ), a 5–10 km wide strip of heavily crevassed ice that flows northward past Minna Bluff, White Island, and ends at the east end of Ross Island where it meets the sea (Fig. 1). It roughly separates the Ross Ice Shelf (RIS) and the McMurdo Ice Shelf (MIS) and exhibits a strong east-west velocity gradient that is responsible for its crevassing. Previous airborne surveys revealed a chaotic crevasse structure superimposed on a set of expected crevasse orientations at 45 degrees to the south-north flow but the dynamics that produced this chaotic structure are poorly understood. The local shear dilatancy associated with multiple generations of crevassing as previously observed in the MSZ can lead to mechanical instability. Consequently, information is needed to better understand and predict its dynamic evolution.

The purpose of this paper is to present the methodology and the results of robotic GPR surveys where data are processed to reveal the velocity field of a small section of the MSZ. This methodology provides the structure of the velocity field on length scales shorter than that of a GPS strain grid or remote sensing approaches. Finally, through imaging at two different frequencies, we provide high resolution GPR imagery of the full thickness of the ice sheet enabling visualization of alignment of surface and basal crevassing and thus allowing us to project the velocity field through the full thickness of the ice sheet.

In Antarctica and elsewhere, ice velocity has been measured using satellite or aerial remote sensing. Radar interferometry derived from European Remote Sensing (ERS-1) of the European Space Agency (Goldstein et al., 1993), RADARSAT synthetic-aperture radar (SAR) data (Rignot et al., 2011; Young and Hyland, 2002; and others), and SAR combined with speckle tracing (Joughin, 2002) are common data sources for velocity estimation. A general approach to velocity estimation using SAR data involves maximizing coherence of SAR imagery patches taken at different points in time, where the patch size in pixels is optimized to achieve maximum coherence and resolution. In Young

Fig. 1. Left) 2016 Make Earth System Data Records for Use in Research Environments (MEaSUREs 2) program velocity contour (Rignot et al., 2017) is superposed on 1999 RADARSAT I Mosaic. The field area is outlined in the black box. Right) 2018 Terra-SAR-X image and MeASURES 2 velocity contours of field area illustrating the location of South Pole overland Traverse (SPoT) route (white line), 2015 GPS field stations (white triangles), and region in which 2014 and 2015 GPR surveys were conducted (black box). RIS denotes the Ross Ice Shelf and MIS denotes the McMurdo Ice Shelf. Velocity contour datasets were produced in the Antarctic Polar Stereographic projection (EPSG 3031) with true scale at 71° S.

and Hyland (2002), for example, a window size of 64×64 pixels in single-look-complex (SLC) images derived from raw SAR data provides a surface resolution of 0.34 km along track and 1.14 km across-track. Rignot et al. (2011) use multiple data sources from 1996 to 2009 – RADARSAT-2 data, Envisat ASAR, Advanced Land Observing Satellite (ALOS) PALSAR, 2000 RADARSAT-1, and 1996 Earth Remote-Sensing Satellites 1 and 2 data – to construct the ice velocity map MEaSUREs for the entire Antarctic continent at a spatial resolution of 450 to 900 m. Given that ice velocity varies by five orders of magnitude over the continent, with the fastest moving glaciers and ice shelves moving up to several kilometers per year, there is a need for higher spatial resolution than the best resolution achievable by remote sensing to understand local dynamics of an ice sheet, particularly in marginal shear zones in which velocity gradients relate directly to stress.

In addition to remote sensing, GPS strain grids (with real-time Kinematic GPS precision) are used to derive velocities and strain rates from ice motion. Patrick et al. (2003) derive velocities and gradients of the heavily crevassed Sørstøl Glacier in East Antarctica from three semi-kinematic GPS strain grids (± 2 cm horizontal and ± 5 cm vertical precision) with a total of 254 points surveyed over two summers. One of the dense grids is placed at 20 m intervals spanning 0.04 km^2 (100 points), while the other two are placed on 200 m and 300 m grids, respectively. Strain rate tensors computed from the densest of these grids are consistent with observed crevassing. While GPS monitoring complements remote sensing to provide high resolution velocity, local deviations in the velocity field within a survey area require an extremely dense GPS grid, and both safety protocols and required density prevent establishing such a dense grid within a heavily crevassed shear

zone.

Arcone et al. (2016) describes initial findings from our first year (2014) survey of a 28 km^2 region within the shear zone on the western margin of the Ross Ice Shelf near McMurdo Station, Antarctica using robot-towed ground penetrating radar (GPR). The GPS coordinates marking the southwest and northeast corners of the region surveyed are -78.08 South, 168.36 West and -78.03 North, 168.6 East. A second survey of the same region was conducted in 2015. Both the 2014 and 2015 GPR datasets are available on request from the U.S. Antarctic Program Data Center, which has archived (offline) the GPR data collected ([dataset] Ray et al., 2018). Robotic GPR acquisition allows safe surveying of ice sheets where crevasses are bridged by snow. Our 2014 survey is the first known dense GPR grid survey over such a large area, and the radar data provide detailed imaging of firm crevasses to approximately 19 m, englacial ice to 160 m, and the upper 15 m of stratified marine basal ice (Arcone et al., 2016). Additionally, the dense grid survey provides detailed visualization of surface and basal crevasse cross sections and their alignments. The grid survey reveals the extent of long (> 1 km) crevasses on the western and eastern boundaries and provides two or more crossings of crevasses within the more chaotic region between these boundaries.

Our 2015 survey of the same GPS points provides a unique data set for velocity estimation by matching crevasse features between annual datasets. Using radar data from two consecutive seasons, we present a methodology to estimate a velocity field based on matching of crevasses imaged annually using GPR. The crevasse matching approach establishes a local velocity field by interpolating the crevasse velocities thus acquired. Real-time kinematic GPS velocity measurements acquired on

a coarser grid are used to seed the crevasse matching procedure. We apply the methodology to the GPR survey data acquired in two consecutive seasons (2014 and 2015) within the heavily crevassed MSZ.

2. Methods and results

2.1. GPR data acquisition methods

The MSZ flows from the entrance of Byrd Glacier to the south, to the northern end of Ross Island. Satellite imagery (Whillans and Merry, 2001) and direct measurement (J. Scaniello, Raytheon Polar services, pers. comm., 2012) provide estimates of absolute velocities of up to 300 m a^{-1} . Surface crevasses bridged by snow occur to a depth of about 40 m (Delaney and Arcone, 1995; Delaney et al., 2004; Arcone and Delaney, 2000; Koh et al., 2010), and occur at approximately 45 degree strike angles from W-E, although evidence from our surveys show rotated crevasse segments within a 3 km wide chaotic strip in the center of the SZ. Englacial ice at approximately from 40 to 160 m depth shows no sign of crevassing in our study region (Arcone et al., 2016). Arcone et al. (2016) show evidence of spatial correspondence of near surface and basal crevasses suggesting that the firn and basal crevassing fractured coevally and locally by lateral shearing.

We deployed the *Yeti* rover in the MSZ, Antarctica, during Oct – Nov 2014 and Oct-Nov 2015 (Fig. 2). *Yeti* is a four-wheel drive, all-electric, GPS-guided rover with a mass of 77 kg that tows a 68 kg GPR sled. Preceding the 2014 and 2015 deployments, *Yeti* was proven operationally through operations support in Greenland, at the South Pole Station, and within the MSZ (Lever et al., 2013). *Yeti* navigates via a set of user-provided GPS waypoints and executes a proportional-integral control loop to command left and right wheel speeds to minimize heading error as it navigates between waypoints. In the MSZ, *Yeti* operated between GPS waypoints separated by 5 km aligned in the West-East direction. The survey grid of $5 \text{ km} \times 5.7 \text{ km}$ was located just south of the South Pole Overland traverse safe road, and we conducted surveys from W-E and return (E-W) along grid lines separated by 50 m spacing at an average survey speed of 1.47 m/s . Over any given 24-h period, typically 18–22 GPS satellites were in view, and position accuracy was 0.6–0.7 m. Arcone et al. (2016) provides detailed information on the survey grid in relation to landmarks in the region, including past safe crossing roads surveyed as part of the South Pole Overland Traverse.

Each profile was defined by a set of four waypoints. The W-E segment corresponded to waypoints at each end of each 5-km survey line and was followed by an E-W segment 50 m South of the W-E line defined by a second set of two waypoints. In both years, we conducted the

Fig. 2. *Yeti* rover towing 67 kg GPR sled holding a GSSI SIR-30 GPR controller and 400 MHz and 200 MHz antenna.

surveys over seven to twelve days of continuous 24-h operations when weather permitted, swapping batteries and saving GPR files after each out-and-back survey run (2.2 h. run time). Prior to conducting the 100+ line main surveys, we conducted several *Yeti* GPR surveys along the western boundary to ensure that it was crevasse-free. The 2014 main grid was surveyed between Oct 29, 2014 and Nov 9, 2014, and the 2015 surveys were acquired between Oct 26, 2015 and Nov 1, 2015. The use of identical waypoints in each project year provides an Eulerian sampling protocol, where sampled GPS locations remain fixed, but the ice moves between annual surveys.

In addition to GPR surveys, we placed and monitored 29 GPS receivers located on a larger grid around the survey area, which communicated with a fixed base station to provide high accuracy RTK GPS. These receivers were monitored at the beginning and end of each deployment to measure ice velocity and strain. Fig. 1 shows the location of the GPR stations from 2014 data and denotes $5 \text{ km} \times 5.7 \text{ km}$ the GPR survey area. Note from Fig. 1 that five of the GPS receivers were placed within the GPR survey area.

We used a GSSI SIR-30 32-bit two-channel control unit and model 5103 “400 MHz” and Model 5106A “200 MHz” antenna units to conduct the GPR surveys. The 400 MHz data are used for velocity field estimation in this paper. The SIR-30 unit simultaneously acquired GPS using a separate antenna from that used for robot navigation, and these GPS data – and not data from the robot GPS receiver used for navigation – were recorded and used to locate GPR traces. *Yeti*’s tracks normally deviated only 1–2 m from a straight line between the two end waypoints (Fig. 3), with infrequent excursions of 3–5 m. Subsequent deployments suggest that the most likely cause of these excursions is GPS ground effects from terrain that dips in elevation caused by compressive forces within the SZ. In deployments subsequent to 2015, the radar GPS antenna was mounted 2–3 ft off the ground, which minimized these ground effects.

Arcone et al. (2016) details the radar configurations and settings for the 2014 survey, which are summarized here for the 400 MHz antenna. Radar antenna impedance loading by the snow is minimal and so the dominant frequencies within the radiated pulse spectra are close to the 400 MHz center frequency. The transmitted pulse is $1\frac{1}{2}$ cycles with a $- + -$ polarity sequence. Pulse lengths in firn at about 40 m depth ($\epsilon_r \approx 2.4$) at 400 MHz are approximately 0.72 m, providing an interface resolution of 0.36 m at this depth. Antenna polarization was perpendicular to transect directions. The $\epsilon_r = 1.8$ for near-surface firn provides a wide, two-way 3-dB beamwidth that narrows to 45° in the electric field plane (parallel to the antennas) and 92° in the magnetic field plane (along transect and perpendicular to the antennas) in ice ($\epsilon_r = 3.18$) providing $\sim 10 \text{ dB}$ of round-trip gain in the normal direction and strong sensitivity to out-of-plane reflections and diffractions (Arcone, 1995). In both years, we recorded $20 \text{ traces sec}^{-1}$, or given a robot speed of

Fig. 3. *Yeti* tracks on a 5-km survey line in the MSZ, 2014 showing typical lateral deviation in a survey line.

1.47 m/s, one trace every 7.4 cm. This spatial sampling allows stacking in post processing to increase signal-to-noise ratio (SNR), although in the derivation of velocity field presented here, stacking is not used, as surface crevasses from which crevasse matches are derived are clearly visible in the data record without stacking. The time ranges of 200 ns at 400 MHz in 2014 and 800 ns in 2015 establish listening depths of ~ 19 m (2014) and 76 m (2015). In both survey years, a 2200 ns time range was used for the 200 MHz antenna. We recorded 4096 32-bit samples-trace⁻¹ for each antenna and used a time variable gain to approximately correct for spherical beam spreading loss. We estimate an error of ± 5 ns in picking any 200 MHz event and ± 1 ns for any 400 MHz event. Additional details regarding GPR operation are provided in [Arcone et al. \(2016\)](#). GPS coordinates are recorded with GPR data at 1 Hz providing one coordinate per 20 traces. GPR coordinates are interpolated linearly between traces to associate a GPS coordinate with each recorded GPR trace. The robot is programmed to move at constant speed justifying linear interpolation of GPS coordinates.

2.2. Methods and results of deriving velocity field from GPR data

The 400 MHz GPR data were labeled to mark and tabulate the GPS location of crevasse crossings characterized by a sagging snow bridge, clear void, and hyperbolic diffractions. Prior to labeling, 2014 data were bandpass filtered with a triangular finite-impulse response (FIR) filter between 250 and 550 MHz. The 2015 data were further processed owing to the longer time range; these data were filtered with a triangular FIR filter between 250 and 550 MHz and interpolated to a depth of ~ 20 m in order to improve SNR in the radargram. [Fig. 4](#) shows labeled crevasse crossings from each of 106 survey lines in 2014 and 104 survey lines in 2015. [Fig. 4](#) also shows the velocity field derived from the GPS strain grid. Red dots on the crevasse map are 2014 crevasse labels and blue dots are 2015 crevasse labels. Isotachs derived from GPS data show a relatively smooth transition from an ice velocity of ~ 200 m/year on the western boundary to ~ 450 m/year on the eastern boundary.

The overlay of hand-labeled crevasse crossings from the annual surveys in [Fig. 4](#) provides maps of nearly the full length (> 1 km) of a number of crevasses that appear at regular intervals on echelon on the western and eastern boundaries of the SZ as well as smaller crevasse segments in a chaotic region between the two boundaries. Eulerian sampling, however, does not guarantee that crevasses are crossed at the same point in each year.

In labeling crevasses, no attempt was made to label the same number of sections per crevasse in each annual dataset, nor to project the location of an individual cross-section from 2014 to 2015 prior to labeling. The data were labeled a line at a time according to visible crevasses within a radargram using computer code that enables a user to select a crevasse location with a mouse click. Nonetheless, from the labeled crevasse sections, one can clearly match crevasses on the western and eastern boundaries as they move to the north from one season to the next. The long red (2014) and blue (2015) crevasse sections within the ellipse in [Fig. 4](#) highlight an example corresponding crevasse pair in two consecutive years. [Fig. 5](#) shows four example radargram sections of matched cross sections of this eastern boundary crevasse, comprising 10 sections in 2014 and 9 in 2015, and indicating consistency of crevasse geometry over one year. Note the commonality in the irregular depth of the crevasse along its length and in the end condition (the last cross-section of each crevasse in [Fig. 5](#)).

Within the chaotic zone characterized by shorter crevasse segments, matching is more difficult. In order to understand the dynamics of crevassing within this zone, we developed a crevasse matching algorithm as follows. We hand select matching crevasse segments from 2014 to 2015 based on similar patterns seen in both datasets - within the global velocity field and in consistency of the crevasse appearance (width and depth) measured from radargrams of crevasse cross sections ([Jordan, 2017](#)). We created a vector field based on these manually selected points by connecting the 2014 crossing to the nearest 2015 crossing point. We then use the global velocity field derived from the GPS strain grid ([Fig. 4](#)) to project the movement of each 2014 manually selected crevasse crossing. We project the annual movement along an

Fig. 4. (left) GPS location of hand-labeled crevasse crossings identified from 2014 and 2015 400 MHz GPR data. Red dots are 2014 crevasse labels and blue dots are 2015 crevasse labels. (right) Derived velocity contour plot from 2015 GPS field campaign in the region including the survey grid and the larger grid of GPS stakes. Four of the crevasse cross sections contained in the ellipse are shown in [Fig. 5](#). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2014:

2015:

Fig. 5. Matched cross-sections of a crevasse mapped in 2014 (left) (4 of 10 sections) and 2015 (right) (4 of 9 sections). The crevasse cross sections are contained in the ellipse in Fig. 4. E-W sections are mirrored to reflect robot motion direction during surveys. The last section corresponds to the eastern-most cross section. Each section is comprised of ~ 1500 traces acquired. Traces are acquired by the SIR-30 at 20 traces/s while the robot is traveling 1.47 m/s. Thus 1500 traces equates to a distance of ~ 110 m. The radar listening depth is ~ 20 m. While Eulerian sampling does not guarantee crossings in the same location in consecutive years, the relative depth and width of a crevasse along its length along with terminus features allows definitive matching of crevasse from 2014 to 2015.

arc centered at the 2014 crossing in the direction of the 2015 crossing. In other words, we use the magnitude of the velocity field derived from the GPS strain grid, and the direction obtained by matching 2014 and 2015 crevasse cross sections to project where the 2014 crossing would occur in 2015, given the local direction of flow. We validate that the

2014 crevasse crossing corresponds to a feature in the 2015 data based on the physical appearance of cross-sections and proximity to a similar 2015 crevasse section of consistent appearance. In this step, we note that owing to Eulerian sampling, the crossings points do not necessarily correspond exactly as indicated pictorially in Fig. 6 (North is up in this

Fig. 6. Illustration of worst-case error bounds in matching crevasse crossings. Solid red circles denote crevasse crossing points labeled in 2014. The yellow arc is an estimate of where that point moved based on the global velocity interpolated from the GPS strain grid. The solid blue markers indicate an actual 2015 crossing. (top) indicates the general case, where 2014 crossings are well correlated with 2015 crossings. (bottom) indicates that the worst-case error occurs when the projected 2014 crossing lies halfway between two actual 2015 crossing points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

pictorial figure.) In Fig. 6, the solid red circles denote crevasse crossing points labeled in 2014. The yellow arc is a projection (estimate) of where that point moved based on the global velocity interpolated from the GPS strain grid. The solid blue markers indicate an actual 2015 crossing. The direction and magnitude of velocity calculated by crevasse matching via the nearest 2015 crossing incurs error owing to

Eulerian sampling. Fig. 6 (left) indicates the general case, where 2014 crossings are well correlated with 2015 crossings. Fig. 6 (right) indicates that the worst-case error occurs when the projected 2014 crossing lies halfway between two actual 2015 crossing points. Given a line spacing of 50 m, the horizontal and vertical separation of crossing points along a crevasse is 50 ± 4 m, and the worst case error (Fig. 6

Fig. 7. Top - Hand selected matches between 2014 and 2015 crevasse crossings establishing a velocity vector field. Bottom - 2014 crevasse crossings (denoted by red x), projected locations of these crossings to 2015 based on the magnitude of the velocity field derived from the GPS strain grid (black x intersecting magenta circle segments), and closest actual crossing (blue x) from 2015 data. North-south and west-east distance indicate the relative distance from the origin of the coordinate system over which the calculated projected crossing location, with (0,-6000) corresponding to the GPS coordinate (-168.36 long, 78.03 lat) and the (-4000, 0) coordinate corresponding to the GPS coordinate (-168.52 long, 78.06 lat). North is down. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 8. Velocity field derived from crevasse matching. Hand selected matches of crevasse crossings from 2014 to 2015 are interpolated across the area of the GPR survey. North is down.

right) is 3 to 6 degrees.

The velocities of selected crevasse cross sections matched using the approach described in section above are shown in Fig. 7. Fig. 7 (top) shows the hand-selected matches from among the calculated velocity magnitude and velocity vector. Fig. 7 (bottom) shows estimated crevasse locations based on projecting 2014 crossing locations to 2015 using the velocity field estimated using the GPS strain grid along. Actual 2015 crossing locations are also shown (blue 'x'). In these figures, any matched crevasse segments whose velocity deviates by more than a magnitude of 25 m/s from that projected based on the GPS strain grid are rejected, comprising 13 points of 170 matching sections selected.

Crevasse matching provides a dense set of points for extrapolating the velocity field, shown in Fig. 8. In this figure, any matched crevasse segments whose velocity deviates by more than a magnitude of 25 m/s from that projected based on the GPS strain grid have been rejected as described above, and the remaining velocities are interpolated across the area. The rejection of matched segments outside of the 25 m/s tolerance considers potential error accumulation due to GPS ground effects, error due to Eulerian sampling described above, and number of days between annual samples.

The velocity field derived from crevasse matching varies significantly from that derived from the GPS strain grid in Fig. 4; local velocity gradients disturb the smooth isotachs derived from GPS strain data and are attributed to frequent rotation of crevasse segments within the chaotic band. Moreover, the difference between the projected location of a crossing within the 2015 dataset relative to the measured crossing can vary within the chaotic region by as much as 100 m in Fig. 7. While the isotachs should not be construed to represent streamlines, Fig. 8, which shows the velocity field within the GPS survey grid, suggests that there is some diagonal orientation to the flow. Comparison of the contours of Fig. 8 to the velocity contours from Whillans and Merry (2001), which are overlaid on high resolution visual satellite imagery, shows a general consistency. We note that the derivation of the velocity field in Fig. 8 is rendered possible solely through the robotic acquisition of GPR data and thus is shown only within the GPR area surveyed.

3. Discussion

The local velocity field in Fig. 8, which is derived from 400 MHz radar data, shows local variations/waviness in velocities that are not evident in the velocity field derived from the GPS strain grid in Fig. 5. Arcone et al. (2016) found that crevasses along a sample survey line from the 2014 grid survey are coeval. Subsequent processing of 2015 200 MHz data also shows coeval crevassing. Further processing of the data shows that coeval crevasses appear on echelon on the western and eastern boundary of the shear zone with some crevasse cross sections within the chaotic zone also matching at the surface and within marine ice. Further assessment of coeval crevassing in the region suggests that this non-uniform velocity gradient across the shear zone velocity field may extend to meteoric and marine ice, which extends to a depth of 160 m. Fig. 9 shows crevasse crossings within the marine ice labeled from 2015 200 MHz data (red 'x'). Note that many of these labels comprise a primary crossing plus labels of a number of reflections. Migration of data to reduce reflections proved difficult for the large dataset. Nonetheless, a comparison of the surface crevasses labeled from 400 MHz data (blue 'x') to labeled marine ice crevasses (red 'x') shows that more than half (471 of 927) of the surface crevasse crossings – hand labeled in 2015 data are coeval with a hand labeled marine ice crossing indicating that the velocity field may extend through the ice sheet. Fig. 10 shows a map of these coeval crevasse crossings indicating possible related crevasses across the shear zone within surface and marine ice. Coeval crossings are identified as those crossings whose GPS longitude and latitude match to within an effective distance of 4.4 m and 1.9 m, respectively. Fig. 10 extracts and maps those crossings that are coeval and indicates a large number of coeval crossings, many of which are aligned with surface crevasse segments used to derive the velocity field.

The robotic grid surveys were completed over two consecutive seasons of 7–12 days with 24-h operations, and annual survey of individual lines were separated temporally by 1 year $\pm$ 3 to 7 days. Two to three field team members working in 8-h shifts to swap batteries and transfer GPR data provides human resources to execute over 600 km of surveys in each field season. Since velocity data are reported in m a^{-1} , and all data are not acquired simultaneously, a worst-case error of

Fig. 9. Hand labeled marine ice crevasses and their reflections in 200 MHz data (red 'x') superimposed with hand labeled firn crevasses from 2015 dataset (blue 'x'). North is down. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$\sim 7 \text{ m a}^{-1}$ is attributed to the temporally extended nature of collection of GPR data.

Limitations in the size of the grid surveyed during our 2014 and 2015 field campaigns extend solely from battery capacity of the robot and radar batteries and length of the field season. The robot, which is powered by six lithium ion batteries ($\sim 1500 \text{ Wh}$) can complete a 10 km transect (W-E and E-W) without completely discharging the battery and comes just shy of a 20 km distance for a second transect. Extending range requires an additional bank of three batteries in parallel. Extending battery capacity could improve range between battery exchanges by a factor of two or $\sim 4.4 \text{ h}$ runtime enabling us to collect a similar dataset in less time, weather permitting. As the robots have now been field validated through both science and logistics work over

several seasons, reliable operation indicates that we can progressively increase range of operation. The data thus acquired would have been impossible to acquire by any other means.

Our solar-powered Cool Robot (Ray et al., 2007), which was used for fine grid surveys in 2014, also is capable of towing the radar sled and extends range indefinitely. Between 2014 and a 2017 deployment, we developed solar power for the radar system as well, extending its range of operation to a minimum of 20 h. Beyond battery capacity, data storage on the radar unit constitutes the next limitation in range, and our interface with the radar allows us to store up to 256 GB of radar data, or over 450 km of radar data at 20 scans/s. GPS waypoint following proves adequate for radar surveys. Sastrugi in the survey region proved to have no significant effect on robot operation.

Fig. 10. Coeval marine ice and firn crevasse sections from 2015 derived from composite map of surface and marine ice crevasses of Fig. 9. Coeval crossings are identified as those crossings whose GPS longitude and latitude match to within an effective distance of 4.4 m and 1.9 m, respectively.

The most significant source of error in local velocity field calculation from crevasse mapping is that of projecting the location of a crevasse section from one annual survey to the next. While the error is small (estimated at a worst-case of ± 4 m based on spacing between survey lines), it is possible to reduce the error effectively to zero by mapping each individual crevasse encountered, rather than conducting a full grid survey. Efforts are underway to develop an autonomous crevasse detection algorithm such that, once detected, the robot would map the crevasse through a local grid placed over the crevasse with survey lines spaced at 5–10 m. This would effectively allow more crevasse crossings and would allow mapping of a crossing from one year to the next to within ± 1 m, which in turn allows for more precise matching of the crevasse between annual surveys.

4. Conclusions

The methodology described in this paper uses robotic-acquired GPR data to estimate a velocity field in a local region within the MSZ. While isotach maps should not be construed to represent streamlines, the data suggest that there is a diagonal orientation to flow. Although surface crevasses are mapped to derive a velocity field in this paper, coeval surface and marine ice crevassing suggest that the results may be approximately true for the meteoric and marine ice. The methods can be used to ground truth remote sensing data or to provide a higher resolution map of ice movement in local regions than is possible to estimate using remote sensing products.

Authors statement

Jordan: Methodology, Software, Validation, Investigation, writing, visualization.

Ray: Conceptualization, supervision, project administration, funding acquisition, data analysis, writing.

Arcone: Conceptualization, writing: review and editing, data analysis, resources.

Kaluzienski: software, visualization, fieldwork, data analysis, writing: review and editing.

Walker: Formal analysis, data curation, fieldwork.

Lever: Project administration, fieldwork.

Koons and Hamilton: Project administration, fieldwork, supervision, funding acquisition.

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References

- Arcone, S.A., 1995. Numerical studies of the radiation patterns of resistively loaded dipoles. *J. Appl. Geophys.* 33, 39–52. [https://doi.org/10.1016/0926-9851\(95\)90028-4](https://doi.org/10.1016/0926-9851(95)90028-4).
- Arcone, S.A., Delaney, A.J., 2000. GPR images of hidden crevasses in Antarctica. In: *Proc., 8th Internat. Conf. on Ground-Penetrating Radar*, pp. 760–765.
- Arcone, S.A., Lever, J.H., Ray, L.E., Walker, B.S., Hamilton, G., Kaluzienski, L., 2016. Ground-penetrating radar profiles of the McMurdo Shear Zone, Antarctica, acquired with an unmanned rover: interpretation of crevasses, fractures, and folds within firm and marine ice. *Geophysics* 81 (1), WA21–WA34.
- Delaney, A.J., Arcone, S.A., 1995. Airborne crevasse detection with ground-penetrating radar: U. S. Army ERDC Cold Regions Res. and Eng. Lab. In: *CRREL Special Report*, pp. 95–97.
- Delaney, A.J., O'Bannon, A., Wright, J., Arcone, S.A., 2004. Crevasse detection with GPR across the Ross Ice Shelf, Antarctica. In: *Proc., 10th Internat. Conf. on Ground-Penetrating Radar*, pp. 777–780.
- Goldstein, R.M., Engelhardt, H., Kamb, B., Frolich, R.M., 1993. Satellite radar interferometry for monitoring ice sheet motion: application to an Antarctic ice stream. *Sci.-NY* Then Washington 262, 1525–1530.
- Jordan, M., 2017. Characteristics of *r_n* crevasses in the McMurdo shear zone. In: *Master's Thesis*. Thayer School of Engineering, Dartmouth College and Helmut Schmidt University.
- Joughin, I., 2002. Ice-sheet velocity mapping: a combined interferometric and speckle-tracking approach. *Ann. Glaciol.* 34 (1), 195–201.
- Koh, G., Lever, J., Arcone, S., Marshall, H.P., Ray, L., 2010. Autonomous FMCW radar survey of Antarctic shear zone. In: *Proc. 13th International Conf. On Ground Penetrating Radar*.
- Lever, J.H., Delaney, A.J., Ray, L.E., Trautmann, E., Barna, L.A., Burzynski, A.M., 2013. Autonomous gpr surveys using the polar rover yeti. *J. Field Robot.* 30 (2), 194–215.
- Patrick, B.A., Corvino, A.F., Wilson, C.J., 2003. Ice-flow measurements and deformation at marginal shear zones on Sørstøl Glacier, Ingrid Christensen Coast, East Antarctica. *Ann. Glaciol.* 37 (1), 60–68.
- Ray, L.E., Lever, J.H., Streeter, A.D., Price, A.D., 2007. Design and power management of a solar-powered “cool robot” for polar instrument networks. *J. Field Robot.* 24 (7), 581–599.
- Ray, L.E., Arcone, S., Kaluzienski, L., Koons, P., Lever, J., Walker, B., 2018. Ground Penetrating Radar Grid Survey of the McMurdo Shear Zone. U.S. Antarctic Program Data Center <https://doi.org/10.15784/601102>.
- Rignot, E., Mouginot, J., Scheuchl, B., 2011. MEaSUREs InSAR-based Antarctica ice velocity map. *Science* 333, 1427–1430.
- Rignot, E., Mouginot, J., Scheuchl, B., 2017. Measures Insar-Based Antarctica Ice Velocity Map, Version 2. NASA DAAC at the National Snow and Ice Data Center, Boulder, CO.
- Whillans, I.M., Merry, C.J., 2001. Analysis of a shear zone where a tractor fell into a crevasse, western side of the Ross Ice Shelf. *Antarctica: Cold Regions Sci. Technol.* 33, 1–17. [https://doi.org/10.1016/S0165-232X\(01\)00024-6](https://doi.org/10.1016/S0165-232X(01)00024-6).
- Young, N.W., Hyland, G., 2002. Velocity and strain rates derived from InSAR analysis over the Amery Ice Shelf, East Antarctica. *Ann. Glaciol.* 34 (1), 228–234.

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14. ABSTRACT The McMurdo shear zone (MSZ) is strip of heavily crevassed ice oriented in the south-north direction and moving northward. Previous airborne surveys revealed a chaotic crevasse structure superimposed on a set of expected crevasse orientations at 45 degrees to the south-north flow (due to shear stress mechanisms). The dynamics that produced this chaotic structure are poorly understood. Our purpose is to present our field methodology and provide field data that will enable validation of models of the MSZ evolution, and here, we present a method for deriving a local velocity field from ground penetrating radar (GPR) data towards that end. Maps of near-surface crevasses were derived from two annual GPR surveys of a 28 km ² region of the MSZ using Eulerian sampling. Our robot-towed and GPS navigated GPR enabled a dense survey grid, with transects of the shear zone at 50 m spacing. Each survey comprised multiple crossings of long (> 1 km) crevasses that appear in echelon on the western and eastern boundaries of the shear zone, as well as two or more crossings of shorter crevasses in the more chaotic zone between the western and eastern boundaries. From these maps, we derived a local velocity field based on the year-to-year movement of the same crevasses. Our velocity field varies significantly from fields previously established using remote sensing and provides more detail than one concurrently derived from a 29-station GPS network. Rather than a simple velocity gradient expected for crevasses oriented approximately 45 degrees to flow direction, we find constant velocity contours oriented diagonally across the shear zone with a wavy fine structure. Although our survey is based on near-surface crevasses, similar crevassing found in marine ice at 160 m depth leads us to conclude that this surface velocity field may hold through the body of meteoric and marine ice. Our success with robot-towed GPR with GPS navigation suggests we may greatly increase our survey areas.					
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*Dartmouth College
Thayer School of Engineering
Hanover, NH 03755*

*University of Maine
School of Earth and Climate Science
Orono, ME 04469*

*Cold Regions Research and Engineering Laboratory
U.S. Army Engineer Research and Development Center
72 Lyme Road
Hanover, NH 03755*