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Robotic Ground-Penetrating-Radar (GPR) Surveys to Support the 2014 Greenland Inland Traverse

James H. Lever, Zoe R. Courville, and Douglas A. Punt

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Robotic Ground-Penetrating-Radar (GPR) Surveys to Support the 2014 Greenland Inland Traverse

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Abstract

The National Science Foundation operates the Greenland Inland Traverse (GrIT) to resupply Summit Station, which is situated at the peak of the Greenland ice cap. Prior to its springtime departure from Thule Air Base in northwest Greenland, GrIT's Strategic Crevasse Avoidance Team (SCAT) conducts ground-penetrating-radar (GPR) surveys along the first 100 km of the route to chart a safe course around subsurface crevasses that could jeopardize the safety of vehicles and personnel. We deployed the polar rover *Yeti* during 2014 to supplement SCAT's survey capabilities. *Yeti* executed 23 autonomous GPR surveys, covering 94 km of terrain. The resulting data allowed us to map hundreds of subsurface crevasses and contributed to SCAT's successful charting of a safe route for GrIT. These were the first robotic surveys that directly supported concurrent manual crevasse surveys. This report describes the techniques used during *Yeti*'s 2014 deployment, the survey results obtained, the main contributions of *Yeti* to SCAT's efforts, and recommendations to improve the efficiency of robotic crevasse surveys to aid manual ones.

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Preface

This study was conducted for National Science Foundation, Division of Polar Programs (NSF-PLR), Arctic Research Support and Logistics (RSL) Program under Engineering for Polar Operations, Logistics, and Research (EPOLAR) EP-ARC-14-12, “Support for GrIT.” The technical monitors were Renee Crain, RSL Associate Program Manager, and Patrick Haggerty, RSL Program Manager, NSF-PLR.

The work was performed Dr. James H. Lever (Force Projection and Sustainment Branch, Dr. Sarah Kopczynski, Chief), Dr. Zoe Courville (Terrestrial and Cryospheric Sciences Branch, J. D. Horne, Chief), and Douglas Punt (Engineering Resources Branch, Jared Oren, Chief), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Jason Weale was the program manager for EPOLAR. Dr. Loren Wehmeyer was Chief of the Research and Engineering Division of ERDC-CRREL. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Robert Davis.

The authors gratefully acknowledge the hands-on support and generous spirit of the entire Strategic Crevasse Avoidance Team (SCAT): Forest McCarthy, Allan Delaney, Robin Davies, Galen Dossin, and Jen Mercer. We would also like to thank Geoff Phillips and the rest of the Greenland Inland Traverse (GrIT) crew for helping us mobilize and demobilize our equipment, work space, and living quarters. Furthermore, we thank Professor Laura Ray for providing *Yeti* to advance operational crevasse detection.

COL Bryan S. Green was Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Acronyms and Abbreviations

ATV	All-Terrain Vehicle
CRREL	U.S. Army Cold Regions Research and Engineering Laboratory
EPOLAR	Engineering for Polar Operations, Logistics, and Research
ERDC	Engineer Research and Development Center
GIS	Geographic Information System
GPR	Ground-Penetrating Radar
GPS	Global Positioning System
GrIT	Greenland Inland Traverse
GSSI	Geophysical Survey Systems, Inc.
NSF	National Science Foundation
PLR	Division of Polar Programs
RSL	Research Support and Logistics
SCAT	Strategic Crevasse Avoidance Team

Executive Summary

Objectives

The National Science Foundation (NSF) operates the Greenland Inland Traverse (GrIT) to resupply Summit Station, located at the peak of the Greenland ice cap, from Thule Air Base in northwest Greenland. GrIT has undertaken resupply missions nearly each spring since 2008. The first 100 km of the route includes numerous subsurface crevasses that pose safety hazards for vehicles and personnel. The Cold Regions Research and Engineering Laboratory (CRREL) annually analyzes pre-season satellite imagery to map visible crevasses along the route corridor. GrIT then fields its Strategic Crevasse Avoidance Team (SCAT) to prospect and verify a safe route by using ground-penetrating radar (GPR).

In 2014, pre-season satellite images were poor quality and did not reveal crevasses along many critical route sections. We therefore supplemented SCAT's capabilities by fielding the polar rover *Yeti* to conduct autonomous GPR surveys. We met both objectives of the surveys: (a) to enhance SCAT's operational efficiency and (b) to conduct systematic surveys over crevassed areas to validate alternate remote-sensing platforms.

Results

Yeti is an 81 kg, 4-wheel drive, battery-powered rover co-developed by Dartmouth College and CRREL (cover photo). In 2014, *Yeti* executed 23 autonomous GPR surveys, covering 94 km of terrain, and the resulting data allowed us to map hundreds of subsurface crevasses. *Yeti's* ability to conduct continuous, gridded surveys across closely spaced crevasses was particularly helpful to delineate safe corridors and to ground truth pre-deployment satellite imagery. Specifically, *Yeti* surveys aided SCAT as follows:

- Dismissed a potential northern corridor through closely spaced crevasses near the start of the route (B0). *Yeti* conducted these surveys prior to SCAT's operational availability and likely saved SCAT two survey days to obtain comparable information.
- Demonstrated that older visual-band satellite images were more reliable than recent radar-satellite images for mapping 2014 crevasses.

- SCAT used this result throughout its 2014 surveys to select the most promising paths through choke points.
- Found a crevasse-free route alignment near B5 via a late-evening survey. This saved SCAT 2 hr and freed it to plan its next-day surveys.
 - Dismissed a potential corridor through curved crevasses near B6. These *Yeti*-gridded surveys freed SCAT to explore and discover a new alignment around the curved crevasses and probably saved SCAT a day of very difficult survey work.
 - Helped to delineate the entrance and boundaries of a new corridor through tightly spaced parallel crevasses B8 to B9. *Yeti* conducted these surveys concurrent with SCAT surveys and saved SCAT approximately 4 hr.
 - Substituted for repeat surveys along promising corridors. These *Yeti* repeat surveys freed SCAT up to prospect along new terrain and saved SCAT approximately two days of repeated surveys needed to verify a safe route.

Yeti's database of georeferenced crevasse crossings will help validate the crevasse-detection capabilities of other remote-sensing platforms, research that could greatly reduce costs to establish safe routes for GrIT and other traverses in Greenland. *Yeti* is well suited to obtain such systematic datasets whereas safety and schedule constraints make this task impractical for SCAT.

Lessons learned

While previous *Yeti* deployments (Lever et al. 2013) helped us to anticipate needs, the 2014 deployment was the first robotic effort directly to support manual crevasse surveys in either Greenland or Antarctica. By comparison, manual GPR surveys to detect crevasses have been used for more than 20 years, and SCAT consisted of a team of highly efficient experts in this process. From our 2014 experience, we learned several important lessons and identified readily achievable refinements to increase *Yeti's* operational efficiency.

The main inefficiency was the need to review GPR files manually to identify crevasse signatures. We reviewed these files each evening and then georeferenced the crevasse locations to include them in SCAT's master map. This delayed availability of the results. Machine-learning algorithms can identify crevasse signatures on GPR files during post-processing and thereby speed up the mapping process (Williams et al. 2012a, 2012b). To

date, Dartmouth, with CRREL encouragement and assistance, has developed these algorithms by using educational grants. Further research is needed to validate the algorithms against Greenland crevasse signatures, and the *Yeti* 2014 dataset is ideal for this purpose.

We have already overcome a second GPR-related inefficiency: data-file limits of the radar controller. The SIR-3000 controller used initially in 2014 had a file limit of 60 MB, which required stopping *Yeti* and saving the radar file every 45 min. For the last four surveys, we swapped the SIR-3000 for the more capable SIR-30, and its 4 GB file limit would have permitted 40 hr of surveys at the same radar settings. We packaged the SIR-30 on a sled with its own battery pack, and recent experience with the same package in Antarctica (Arcone et al. 2016) showed approximately 20 hr of radar-battery endurance. Even the less-expensive SIR-4000 (the SIR-3000's commercial replacement with a 2 GB file limit) could achieve 20 hr of continuous robotic surveys. That is, radar file capacity is no longer a practical limit for *Yeti* surveys.

Yeti displayed exceptional reliability in a polar context, operating at temperatures to -30°C , tolerating overnight snowstorms, and requiring only a few minutes of preparation each morning. A single set of six batteries provided 4 hr, 17 km endurance, and battery swaps were accomplished within a couple of minutes. *Yeti* did experience immobilization on two occasions: once executing an uphill turn in soft snow and once travelling across fresh, deep ruts made by one of the tracked vehicles. Immobilizations in ruts along a proven route allow easy, safe recovery. Immobilizations in remote terrain are more problematic but rare for *Yeti*, and they invariably occur along the programmed course. Nevertheless, addition of a GPS tracker would reduce anxiety over the location of the rover if it is out of radio contact and does not return on schedule.

Conclusions and recommendations

Overall, *Yeti's* autonomous GPR surveys contributed to SCAT's successful effort to find and verify a safe route for GrIT in 2014. The rover was operationally reliable, and the survey results were incorporated into the master map for SCAT route planning and assessment. Direct costs were low: Dartmouth and CRREL contributed the rover and radar equipment, and *Yeti's* deployment leveraged SCAT's support vehicle, second mountaineer, and second GPR operator. *Yeti's* shortcomings derived mainly from the

newness of the mode—these were the first autonomous surveys to support operational crevasse detection directly.

Crevasse conditions along GrIT's route have become more complex in recent years (Burzynski et al. 2012). If this trend continues, it will place exceptional demands on the skill and efficiency of SCAT to prospect and verify a safe route. Therefore, we recommend the following steps to increase *Yeti's* time- and cost-saving contributions to SCAT:

- Implement and verify Dartmouth's crevasse-detection algorithms for operational use in Greenland by using *Yeti's* extensive 2014 dataset as validation.
- Deploy *Yeti* with SCAT in 2017 together with the SIR-30 or SIR-4000 and validated crevasse-detecting algorithms, and assess their impact on survey efficiency.
- Boost *Yeti's* endurance (battery capacity) to 6–8 hr, and add a GPS tracker to extend its range of independent operation.

1 Introduction

1.1 Background

The National Science Foundation (NSF) operates the Greenland Inland Traverse (GrIT) to resupply Summit Station, located at the peak of the Greenland ice cap, from Thule Air Base in northwest Greenland. Departing in early April, GrIT's tractors tow fuel and cargo sleds over natural snow to Summit, a one-way distance of 1200 km, and then return via the same route to Thule in late May for over-winter equipment storage.

The first 100 km of the route onto the main ice cap is ridden with crevasses—deep cracks in the snow and ice that pose safety hazards for vehicles and personnel. Some crevasses are visibly obvious from the snow surface, but most others are covered by 1–5 m thick snow bridges that obscure the underlying voids. During the summer months, snow bridges can sag or collapse, rendering the crevasses visible on satellite imagery. However, new crevasses can form during the 8-month interval from summer's end to GrIT's departure, and the quality of summer optical imagery depends strongly on the degree of bridge sagging, the sun angle relative to crevasse orientation, the timing of new snowfall, and the extent of cloud cover over the route.

Since GrIT's inception in 2008, the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) annually helps to establish a safe route through the crevasse region. CRREL requests annual satellite imagery along the route (typically 0.5 m resolution visual-band, panchromatic images), delineates the visible crevasses, and provides the resulting georeferenced map in a geographic information system (GIS) format (Figure 1). GrIT then fields its Strategic Crevasse Avoidance Team (SCAT) to prospect and verify a safe route by using ground-penetrating radar (GPR) to ensure that no crevasses wider than 0.71 m (28 in.) lie along the route. CRREL helped to develop SCAT's procedures, provided GPR and navigation expertise for several years, and transferred this capability to SCAT personnel. Over GrIT's seven-year existence, crevassing along the route has become more extensive (Burzynski et al. 2012), and several locations require a concerted effort by SCAT to verify a safe corridor (Figure 2).

Figure 1. Crevasse map developed by CRREL using summer 2011 WorldView-2 satellite imagery to delineate visible crevasses (*orange lines*) along the first 70 km of the 2012 GrIT route (*red line*). Thule Air Base is just off the upper-left side of the image.

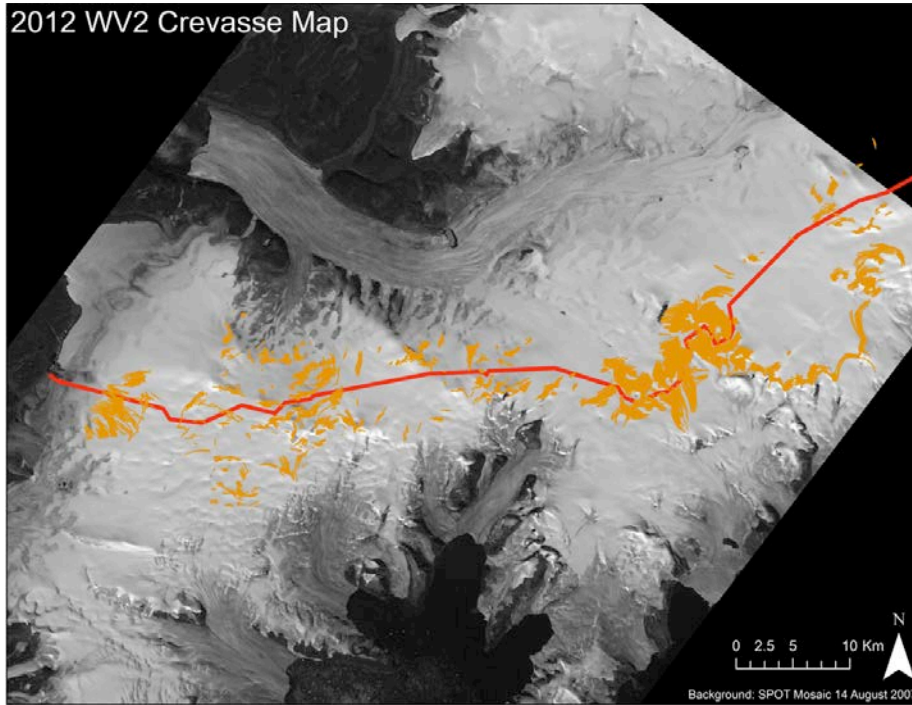
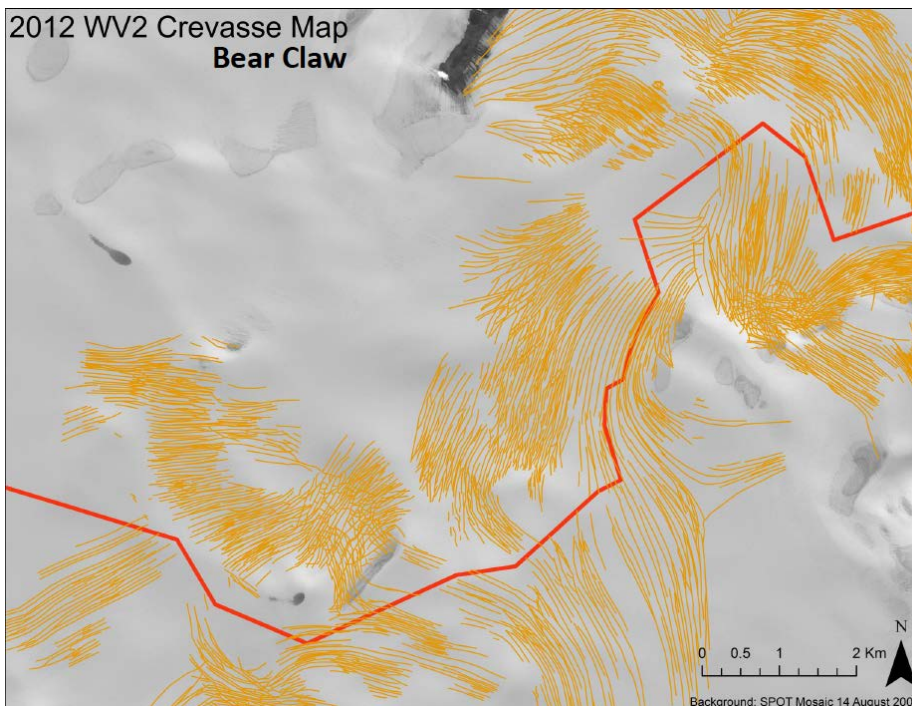


Figure 2. Close-up of route section about 50 km outbound showing extensive, closely spaced crevasses crowding the 2012 GrIT route.



SCAT's primary survey system consists of a 400 MHz GPR antenna mounted on a 6 m long boom pushed in front of a Tucker Sno-Cat tracked vehicle (Figure 3). A Geophysical Survey Systems, Inc. (GSSI), SIR-3000 GPR controller that is mounted in the Tucker generates the GPR pulses, acquires the returns, and displays the resulting time-gated, subsurface reflections in the form of a scrolling radargram. A driver, navigator, and GPR operator sit inside the moving vehicle as the latter interprets the GPR signals in real time to identify the presence of crevasses. A global positioning system (GPS) receiver feeds position data into the GIS software in real time, which allows the driver and navigator to guide the Tucker through the crevasse fields marked on the map. The GPR operator has 3–4 sec to announce the impending arrival of a thinly bridged or wide crevasse before the vehicle itself is on top of it and at risk of collapsing into the void. This operational stressor is compounded by a schedule stressor: GrIT cannot depart until SCAT completes its effort to verify a safe route.

Figure 3. SCAT's manual-survey vehicle consists of a Tucker Sno-Cat equipped with a GPR antenna on a 6 m long boom. An operator interprets the GPR signals in real time to detect the presences of underlying crevasses while a driver and navigator guide the vehicle along the prospective route.



SCAT's challenges in 2014 were greater than in prior years. Summer 2013 WorldView-2 satellite images along the route were of poor quality owing to cloud and snow cover, and CRREL analysts were unable to identify crevasses along many critical sections. CRREL subsequently requested and processed Radarsat-2 images. These images were unaffected by clouds but had a coarser resolution (2.0 m), required terrain-aspect correction to georeference them, and provided crevasse signatures likely influenced by

the thickness and shape of overlying snow bridges. It was not clear that the Radarsat-2 images would provide a reliable basis for SCAT to chart a safe 2014 GrIT route.

1.2 Objectives

We supplemented SCAT's capabilities in 2014 by fielding the polar rover *Yeti* to conduct autonomous GPR surveys. The objectives of the surveys were (a) to enhance SCAT's operational efficiency and (b) to conduct systematic surveys over crevassed areas to validate alternate remote-sensing platforms.

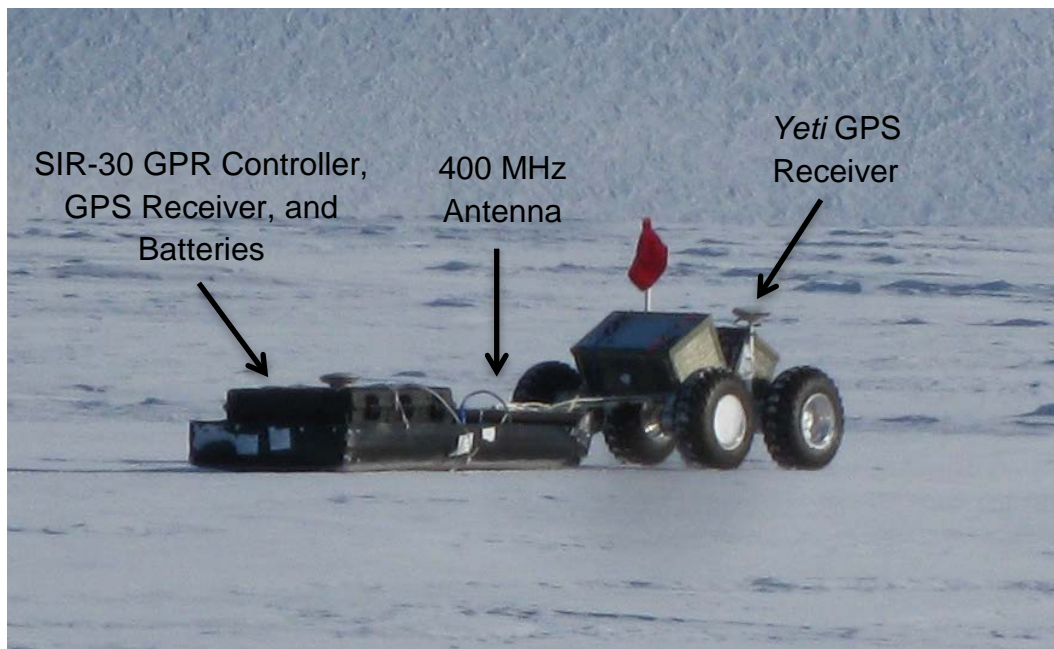
1.3 Approach

We equipped *Yeti* with GPR and programmed it to conduct autonomous surveys using pre-planned GPS waypoints selected based on SCAT's daily survey needs. *Yeti* conducted these surveys initially during SCAT's day trips from Thule and then alongside SCAT in the field. We manually reviewed the GPR data after the surveys, mapped the crevasses detected, and provided the results to SCAT to incorporate into its survey activities. We also archived the georeferenced GPR data for future work to validate alternate remote-sensing platforms.

2 Autonomous Crevasse Surveys

Yeti is a 4-wheel-drive, battery-powered rover that was co-developed by Dartmouth and CRREL to conduct autonomous GPR surveys (Figure 4). It has demonstrated reliable operation and good mobility over snowfields in Antarctica and Greenland (Lever et al. 2013; Barna et al. 2015; Arcone et al., in press). The 81 kg vehicle has a nominal ground pressure of 20 kPa through 0.51 m diameter all-terrain vehicle (ATV) tires. *Yeti* therefore can drive safely over most bridged crevasses to obtain continuous GPR records of crevasse-ridden terrain. It uses a high-quality Novatel GPS receiver to execute preplanned courses by using waypoint navigation. In polar regions, the GPS receiver can typically see 18–20 satellites and achieve a horizontal-position accuracy of less than 1 m.

Figure 4. *Yeti* towing a SIR-30 GPR controller and a 400 MHz antenna in a sled over crevasse-ridden terrain along a prospective 2014 route alignment.



Yeti provides a complementary survey capability to SCAT's manual surveys. It can be programmed to execute linear, grid, or zigzag patterns with a total course length limited to about 17 km, or 4 hr of usable battery life on typically firm polar snow. *Yeti* tows a GPR antenna controlled by either an on-board or sled-mounted radar controller. The GPR controller links the GPS track log of the survey to the acquired radar data so that executed courses and identified crevasse locations can be georeferenced. We post-

process the GPR and GPS data to identify crevasse signatures and to map their locations in GIS.

2.1 Yeti surveys for 2014 GrIT and SCAT

Our objectives for *Yeti's* deployment in 2014 were (a) to enhance SCAT's operational efficiency to seek and verify a safe route through the crevasse zone and (b) to conduct systematic surveys over crevassed areas to validate alternate remote-sensing modes. Owing to the poor or unproven satellite imagery available for 2014, we expected *Yeti* to be particularly helpful when surveying in heavily crevassed areas where several route options might need to be explored. While previous *Yeti* deployments (Lever et al. 2013) helped us to anticipate needs, the 2014 deployment was the first robotic effort directly supporting concurrent manual crevasse detection.

We equipped *Yeti* to use two different GSSI GPR controllers, both connected to a 400 MHz antenna. The smaller and lighter SIR-3000 controller, identical to the one used by SCAT, fit within *Yeti's* onboard battery enclosure. We were very familiar with its operation, including its limited file capacity (60 MB), which dictated manual file saves every 45 min, or about 4 km of course length. This limit is not significant for manual GPR surveys but severely restricts the endurance of autonomous surveys. The SIR-3000 also awkwardly stores GPS track data on a separate drive, which then requires separate post-processing to merge the GPR and GPS data to georeference crevasse signatures.

Anticipating the need for longer surveys to support SCAT, we also equipped *Yeti* to tow the heavier, more capable and more expensive GSSI SIR-30 radar controller. The SIR-30 file limit is 4 GB, or 70 times that of the SIR-3000, and it automatically merges GPR and GPS data for each survey, simplifying the crevasse-mapping process. We built a power supply for the SIR-30 based on the same lithium-ion batteries that power *Yeti* and integrated it within the SIR-30's enclosure. We also built a light-weight sled to tow the enclosure and antenna behind *Yeti*. The 2014 *Yeti* deployment to Greenland was our first experience using a SIR-30 to conduct autonomous surveys. To reduce deployment costs, CRREL provided all of the radar equipment at no cost except to prepare and ship it to Greenland.

SCAT GPR operators Allan Delaney and Zoe Courville established GPR settings for both radar controllers to ensure that the collected radar data were directly comparable to that obtained by SCAT's manual surveys. Two-way travel time was set to 150 ns, 512 samples/scan were recorded at 24–40 scans/s, and a band-pass filter of 125–700 MHz was applied to the raw data. We initially used the SIR-3000 because of our familiarity with that controller. We then switched to the SIR-30 to enable *Yeti* to survey longer courses.

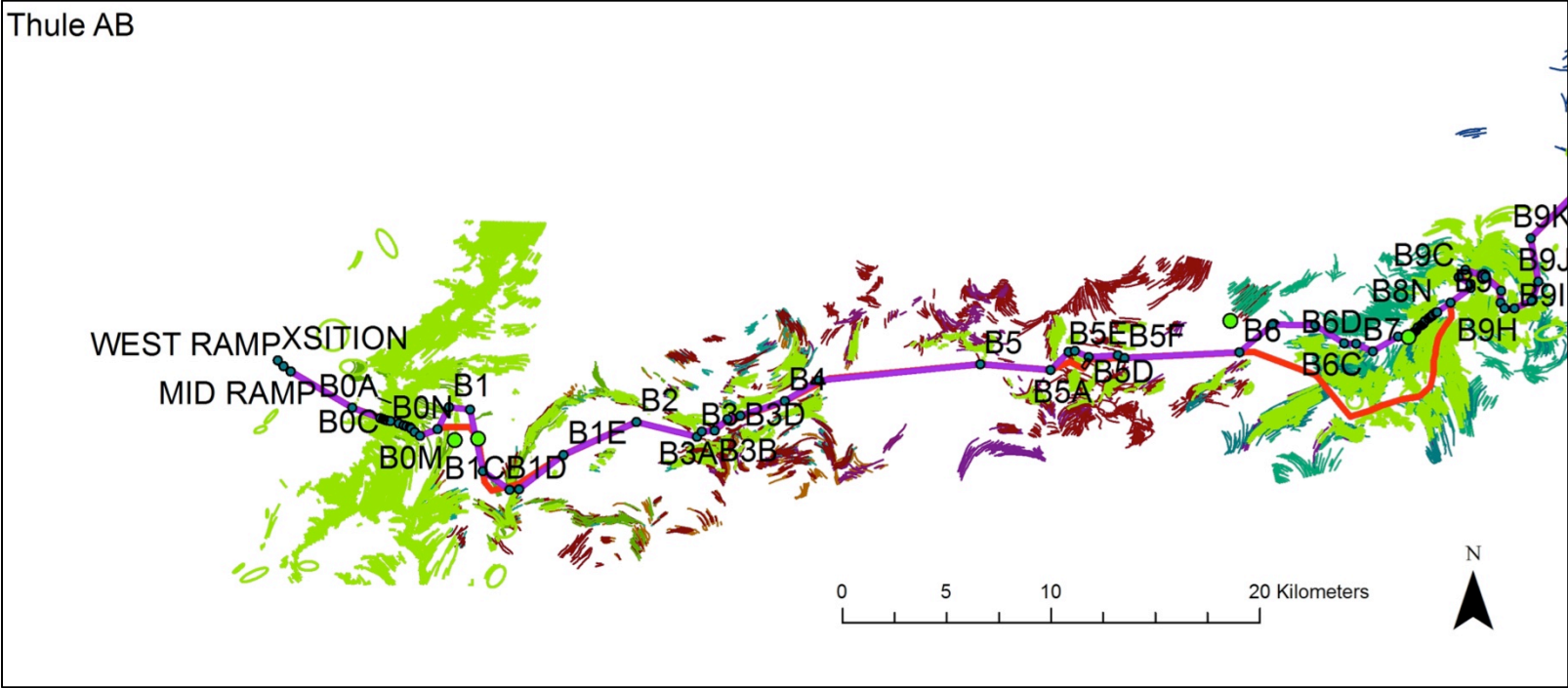
Table 1 summarizes the *Yeti* deployments for GrIT/SCAT14 and Figure 5 shows the area of operation and route segments. Note that the route waypoint labels follow a convention adopted by SCAT. In 2008, SCAT labeled each successive waypoint of the inaugural route as B0, B1, B2, etc. In subsequent years, as SCAT has added new waypoints between two existing waypoints, it has alternated letters and numbers and incremented each accordingly (e.g., waypoints B1A, B1B, B1C, etc., lie successively between waypoints B1 and B2).

We conducted the 11 survey runs from 25 February to 7 March during SCAT day trips from Thule. We conducted the remaining 12 survey runs as part of SCAT's field campaign, based from a mobile camp on the ice cap. *Yeti* executed over 94 km of surveys and mapped hundreds of crevasse locations. During day-trips and field campaigns, we launched and recovered *Yeti* by using SCAT's safety-backup vehicle, a PistenBully 100. SCAT's second mountaineer assisted with *Yeti* preparation and recovery while maintaining his role as safety backup for SCAT's manual surveys. Courville also performed double duty, serving as SCAT's second GPR operator during the day and reviewing *Yeti*'s GPR files each evening to identify crevasse signatures. These synergies, along with Dartmouth's provision of *Yeti* and its support equipment at no charge, helped to keep deployment costs low.

Table 1. The *Yeti* 2014 deployment summary. Locations correspond to route waypoints (Fig. 5).

Date	Location	Pattern	Length (km)	Crevasses Mapped	Comments
25 Feb. 2014	top of ramp	box	7.5	yes (none found)	clean run
26 Feb. 2014	B0 north, 2008 route	grid	4.1	yes	clean run
	B0 north, 2008 route	grid	5.3	yes	clean run
28 Feb. 2014	B0 north, 2008 route	grid	4.8	yes	clean run
	B0 north, 2008 route	grid	3.8	yes	clean run
5 Mar. 2014	B0C-B0D	zigzag	2.2	yes	clean run
	B0D-B0G	zigzag	3.1	yes	clean run
	B1-B0H	grid	2.5	no	lost GPR/GPS when SIR-3000 battery died after long wait
6 Mar. 2014	B0B	zigzag	0.3	no	stuck in deep PistenBully rut from pivot turn
	B0B	zigzag	1.5	yes	repeat course, clean run
7 Mar. 2014	B1-B1A	box	2.2	yes	clean run
12 Mar. 2014	B3C-B3D bowl	zigzag	0.9	yes (none found)	stuck during uphill turn in soft snow, stays out overnight with no ill effects
13 Mar. 2014	B5C-B5D	box	1.4	yes	clean run
14 Mar. 2014	B3-B3D bowl	linear	3.1	yes	clean run
	B6-B6A	box	6.5	yes	clean run
15 Mar. 2014	B6-B6A	box	5.1	yes	clean run
	B5F-B5A camp	zigzag + linear	3.1	yes (none found)	clean run, new route section found
16 Mar. 2014	B6A	box	4.1	yes	clean run
	B6A	box	4.3	yes	clean run
17 Mar. 2014	B6A	grid	9.9	yes	first SIR30 run, <i>Yeti</i> executes grid but SIR-30 file only 14 min long
18 Mar. 2014	B6A	grid	10.8	yes	clean run
19 Mar. 2014	B8_new	zigzag + transit	4.0	yes	clean run to delineate new B8 lane
	B8_new	zigzag + transit	3.9	yes	clean run to delineate new B8 lane

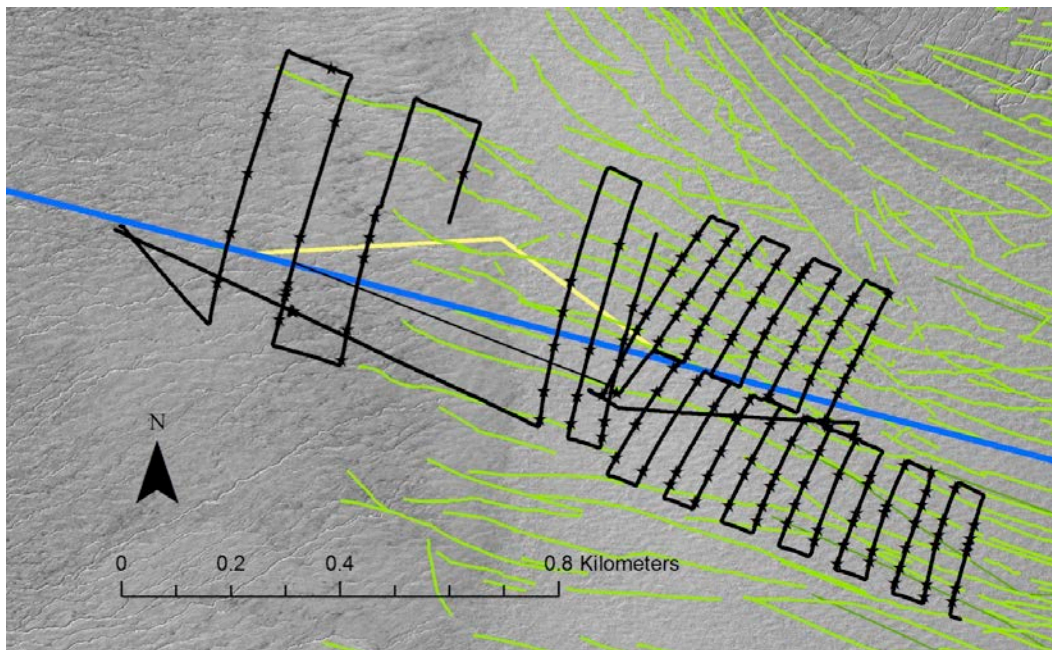
Figure 5. Map of *Yeti's* area of operation during SCAT14, with crevasse fields derived from satellite imagery. The *purple line* shows the final 2014 route with major waypoints labeled (B0A through B9K). The *red line* shows the 2012 route alignment. The 30 km gravel road from Thule Air Base to the ice transition (XSITION) is not shown.



2.2 Day-trip surveys

Day trips from Thule focused mainly on seeking a safe route alignment through the heavily crevassed BO route section, an area dominated by closely spaced parallel crevasses. The 2013 Radarsat-2 imagery suggested that wide, safe lanes through the crevasses might exist north of the 2012 route along an alignment close to the 2008–10 route alignments. We conducted several *Yeti* surveys to assess this possibility (Figure 6). By mapping the resulting crevasse locations, we determined that even the most promising lanes were actually quite narrow and were probably pinched-off by diagonal crevasses. We then reviewed older WorldView-2 imagery, from summer 2011, and it also showed narrow and pinched lanes. These initial surveys helped us to select 24 scans/s for the SIR-3000 as a compromise between survey length and signal quality, leading to a GPR file length limit of 45 min, or a 4 km course length, for that controller.

Figure 6. Four *Yeti* surveys (*black lines*) along the 2008–10 route alignments (*blue and yellow lines*) through the BO crevasse field (Fig. 5). The *Yeti*-mapped crevasses (*black stars*) indicated that the possible lanes were narrow and probably pinched-off by diagonal crevasses. The underlying 2011 WorldView-2 imagery also revealed this crevasse structure (drawn in *green*) whereas the 2013 Radarsat-2 imagery suggested that more promising safe lanes might exist. The varying survey lengths resulted from trials of different GPR scan rates (24–40 scans/s).



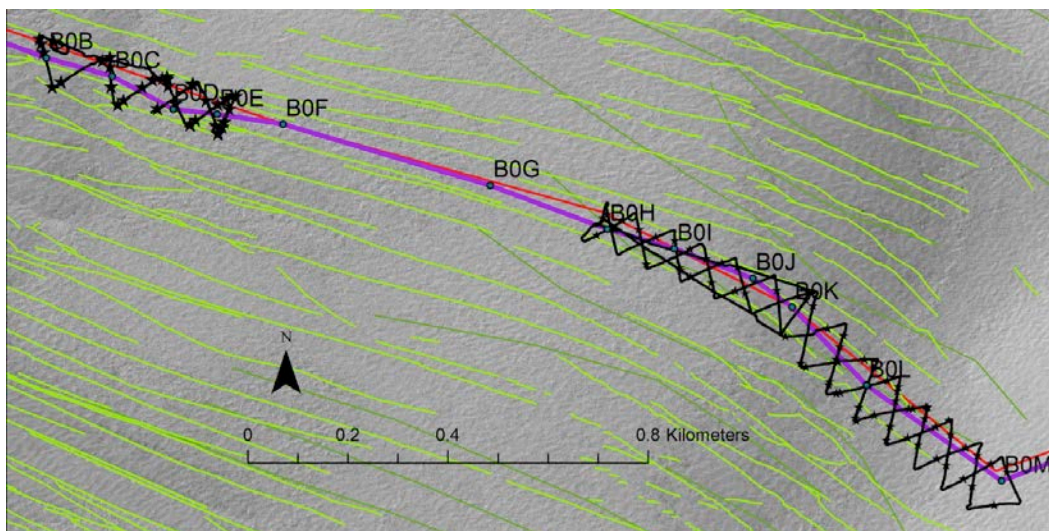
The northern BO *Yeti* surveys produced two important benefits for SCAT. First, they freed SCAT from the difficult task of assessing this alignment option. Unlike *Yeti*, SCAT normally cannot safely cross a series of parallel

crevasses to find the most promising lane. Rather, it uses satellite imagery to select a promising lane and then conducts zigzag surveys to confirm the lane boundaries. For each zigzag survey, SCAT drives roughly 45° to the expected alignment of the crevasse, stops when its GPR locates the crevasse, backs up slightly, then turns 90° and heads towards the expected location of the opposite boundary crevasse across the lane. If the lane is narrow or pinched-off, SCAT must retreat to a safe location outside of the crevasse field, select an alternative lane, and conduct another zigzag survey. Given the safety risks, this can be a tedious and stressful process, and the *Yeti* surveys along the northern B0 option likely saved SCAT two days to obtain comparable information.

Second, the fact that a promising northern lane through the B0 crevasses did not exist produced an important remote-sensing ground truth result: the summer 2011 WorldView-2 imagery, despite being two years older, yielded more accurate and complete crevasse maps than the 2013 Radarsat-2 imagery. SCAT benefited from this lesson to select a successful B0 lane near the 2012 route alignment and subsequently used the older imagery for guidance as it explored deeper into the crevasse zone. Although difficult to quantify, this *Yeti*-obtained ground truth result undoubtedly contributed to SCAT's ultimate success in establishing a safe route in 2014. *Yeti* provided this information before SCAT had fully mobilized for its own day-trip surveys.

The remaining day trips included several *Yeti* surveys along the 2012 route through the B0 crevasse field. As expected, the closely spaced parallel crevasses constrained SCAT's maneuvering room and slowed its survey pace. These *Yeti* surveys helped SCAT to confirm the boundaries of a narrow (approximately 30 m wide) but safe corridor through the B0 crevasses despite the presence of new crevasses not visible on the 2011 imagery (Figure 7). To confirm that any promising corridor is safe for GrIT to use, SCAT must conduct several overlapping surveys to ensure that it has not missed hazardous crevasses. This was the first example where *Yeti* surveys substituted for or complemented SCAT's repeat surveys to confirm a promising corridor.

Figure 7. *Yeti* zigzag surveys (*black*) along the 2012 route (*red*) helped to confirm the boundaries of a narrow but safe corridor through the B0 crevasse field for 2014 (*purple*).



2.3 Field-expedition surveys

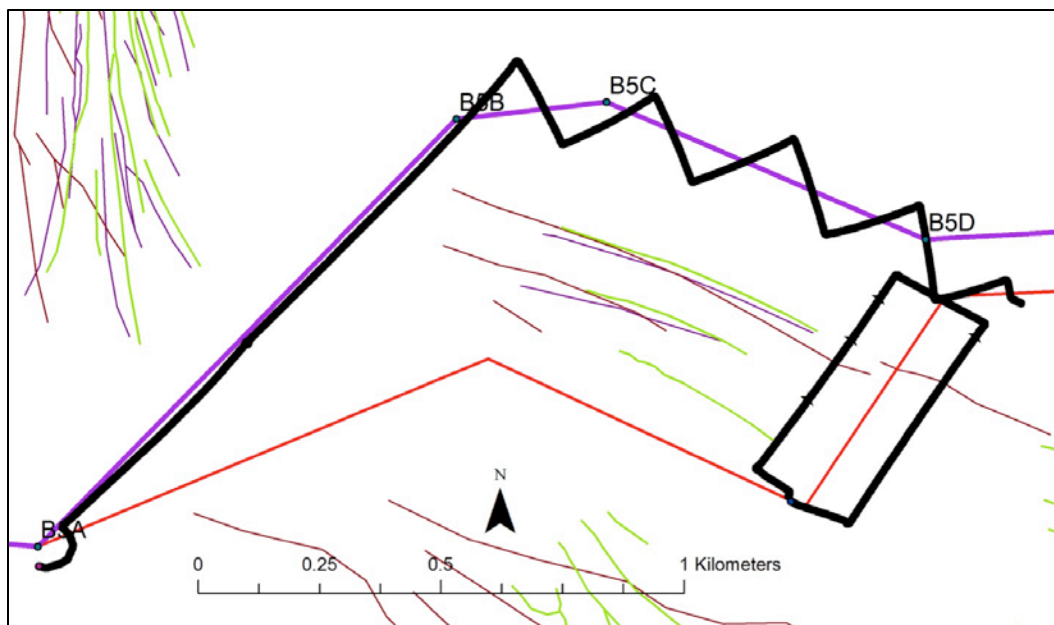
SCAT began its field expedition on 12 March 2014, and *Yeti* accompanied it. We used a mobile science building, the *survey module*, to store battery chargers and other equipment to support *Yeti* surveys. This enabled more efficient operations than staging gear from Thule for the day trips.

We attempted a late-evening survey on 12 March 2014 after making camp. The course included a zigzag pattern across a deep bowl near B3D. *Yeti* did not complete this survey, and we recovered it the following morning—it had broken traction while executing an uphill turn. The rover and onboard equipment suffered no ill effects from a night out at -30°C . Interestingly, *Yeti* also broke traction driving uphill across this same bowl during a survey in 2012 (Lever et al. 2013), suggesting that soft snow is a persistent condition within this topographical feature. Nevertheless, *Yeti* completed a linear survey across this bowl on 14 March 2014 without problems. Uphill turns are more demanding than straight driving for a rover with skid steering (differential wheel speeds), such as *Yeti*, especially when combined with soft snow. This was *Yeti*'s only immobilization in natural terrain during the 2014 deployment.

SCAT first encountered serious difficulties locating a crevasse-free route alignment at the B5 area (Figure 5). *Yeti* conducted two surveys in this area (Figure 8). At SCAT's suggestion, we executed a late-evening, combined zigzag–linear survey back to camp on 15 March 2014 to explore a path around the crevasses that blocked the 2012 route alignment. SCAT

surveyed a different course back to camp. *Yeti's* resulting GPR file contained no crevasse signatures. This survey saved SCAT about 2 hr and allowed it to plan a repeat survey, rather than a more cautious exploratory one, for the next morning. SCAT confirmed this alignment as crevasse free, and it became part of GrIT's 2014 safe route.

Figure 8. *Yeti* conducted two surveys in the B5 area, including a combined zigzag-linear survey that identified a crevasse-free alignment (*purple*) north of the blocked 2012 route (*red*).



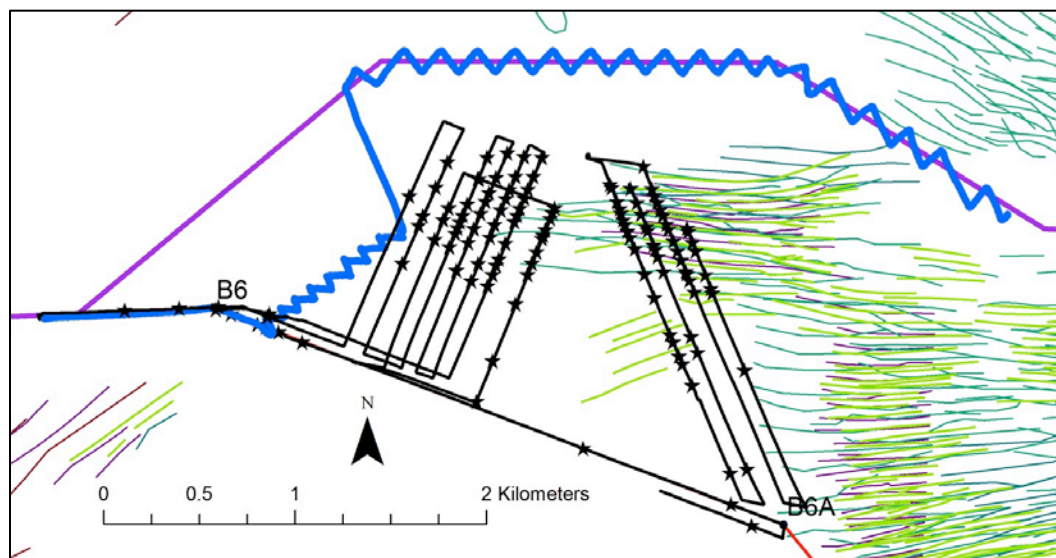
SCAT's most challenging task in 2014 was to seek a crevasse-free alignment from B6 to B9, a region that included several heavily crevassed areas along the 2012 route (Figure 5). Initial manual and *Yeti* surveys indicated that several crevasses crossed the B6–B6A segment although satellite imagery showed that segment to be crevasse free with about 2 km separating the nearest crevasse fields. On 15–18 March 2014, *Yeti* conducted four gridded surveys north of the 2012 route (Figure 9) and was able to confirm that these crevasses actually converged to form a continuous, curved crevasse field that thoroughly blocked the 2012 route. These *Yeti* surveys freed SCAT from the tedious and time-consuming task of attempting to seek a lane through these crevasses, saving SCAT a day of very difficult survey work.

While *Yeti* conducted its first two B6 surveys, SCAT explored southeastward beyond B6A and discovered that crevasses appearing in the satellite imagery to cross the 2012 route actually did not exist or were pinched

closed. SCAT therefore requested that *Yeti* conduct two surveys across crevasses marked in the imagery north of B6A in the hope that these crevasses also were pinched closed. Unfortunately, the *Yeti* data confirmed that numerous wide crevasses did indeed exist (right side of Figure 9), effectively sealing off the 2012 B6–B6A corridor. SCAT’s survey vehicle would not have been able safely to cross many of these crevasses to obtain comparable ground truth data.

Concurrently with *Yeti*’s B6 surveys, SCAT explored a route alignment that passed west and north of the B6 crevasses (blue zigzags in Figure 9). SCAT successfully found a crevasse-free alignment circumventing the B6 crevasses, which produced the key breakthrough to establish a safe route in 2014. Again, by freeing SCAT from the burden of conducting detailed surveys through closely spaced crevasses, *Yeti* allowed SCAT to focus its attentions on alternative route alignments.

Figure 9. *Yeti* conducted four B6–B6A surveys to establish the extent of the crevasse fields that blocked the 2012 route. At SCAT’s request, *Yeti* conducted two of these surveys to confirm that crevasses marked on satellite imagery did indeed exist north of B6A. Concurrently, SCAT explored a route alignment that passed west and north of these crevasses (blue zigzag lines).

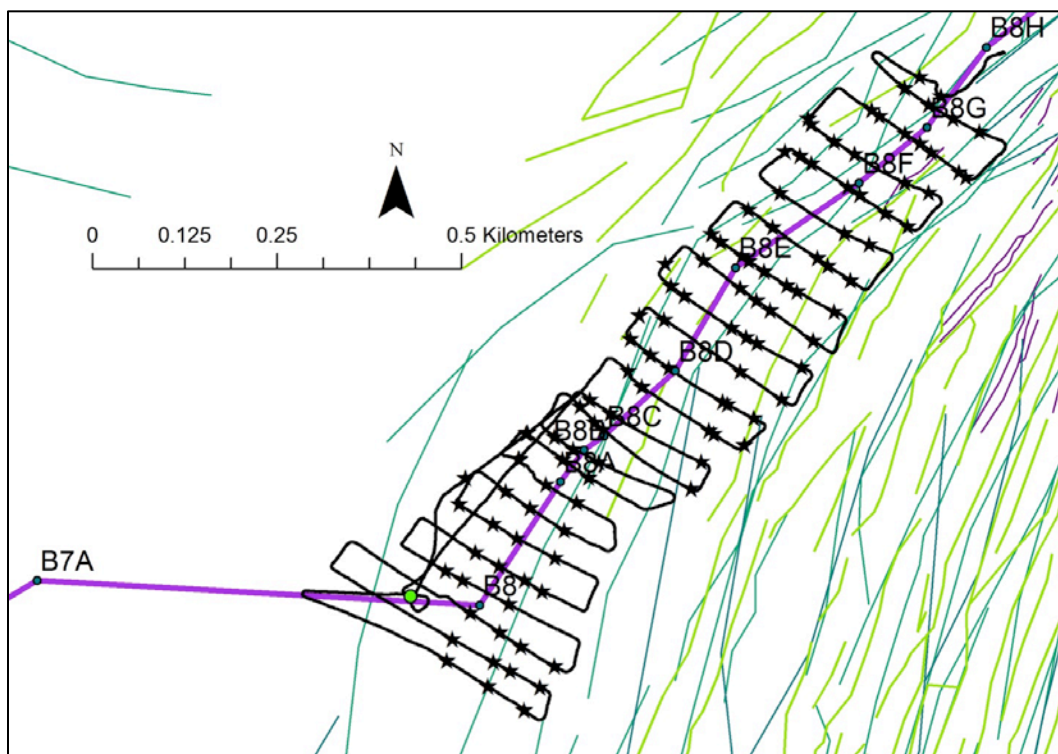


On 18 March 2014, while *Yeti* was completing its B6A surveys, SCAT identified a possible path from B6 to B9 over previously unexplored terrain between two low hills. The 2011 imagery showed an extensive set of parallel crevasses between these hills, yet SCAT found a narrow but crevasse-free lane through to B9. On 19 March 2014, *Yeti* conducted two gridded sur-

veys along this lane to help define its entrance and boundaries and to ensure that no significant crevasses remained undiscovered between SCAT's manual survey courses (Figure 10). SCAT later explored several possible crevasse signatures identified on *Yeti* surveys to ensure that these posed no threat to GrIT tractors. This narrow B8–B9 corridor became part of GrIT14's safe route. *Yeti*'s B8 surveys probably saved SCAT 4 hr of repeat survey work along this narrow corridor.

SCAT continued to explore beyond B9 and determined that the 2012 route was usable and that no tight crevasse fields existed beyond B9.

Figure 10. *Yeti* conducted two gridded surveys on 19 March 2014 (*black lines*) to help define the entrance and boundaries of a narrow lane through parallel crevasses along new route alignment B7A to B9. These surveys help to establish this new corridor as part of the GrIT14 safe route (*purple line*).



3 Discussion

To complement SCAT's manual surveys, we deployed the polar rover *Yeti* in 2014 to conduct autonomous GPR surveys along the heavily crevassed sections of GrIT's route. We met both of our objectives: (a) to enhance SCAT's operational efficiency and (b) to conduct systematic surveys over crevassed areas to validate alternate remote-sensing modes. This section attempts to quantify *Yeti's* contributions to SCAT's ultimately successful effort to establish a safe route for GrIT in 2014. We also provide information on the costs for *Yeti* to achieve these benefits.

3.1 Specific contributions

Yeti made several specific contributions to SCAT's operational efficiency. Its initial day-trip surveys demonstrated that a northern alignment through the B0 crevasses was not feasible, which freed SCAT from the difficult task of assessing this alignment option. For safety reasons, SCAT must necessarily work slowly through parallel crevasses. *Yeti* was able to conduct gridded surveys, crossing numerous crevasses that SCAT would not have been able to cross safely, in an effort to find a promising lane.

Yeti's northern-B0 surveys also demonstrated that summer 2013 Radar-sat-2 imagery was not reliable for identifying crevasse-free terrain and needed to be supplemented with 2011 WorldView-2 imagery. SCAT benefited from this lesson throughout the remainder of its work to seek safe route alignments.

Additional *Yeti* day-trip surveys helped to confirm a safe, narrow lane through the B0 crevasses along the 2012 alignment, a section incorporated into GrIT14's route. Again, because it could conduct surveys across parallel crevasses, *Yeti* reduced the time needed for SCAT to confirm the lane safe for GrIT tractors.

SCAT first encountered serious difficulties locating a crevasse-free route alignment at the B5 area. *Yeti* supplemented SCAT's route-seeking effort by conducting a late-evening survey at B5A that showed no crevasses along a new alignment north of the 2012 route. After SCAT confirmed this alignment as crevasse free, it became part of GrIT14's route. SCAT must survey each route section several times to ensure that it is crevasse free, but *Yeti*

surveys substituted for some of these repeated surveys and thus freed SCAT to prospect along new terrain.

SCAT's most challenging task in 2014 was to seek a crevasse-free alignment from B6 to B9, and it devoted several days of effort to understand changes in the crevasse fields that had occurred since 2012. At SCAT's request, *Yeti* conducted four gridded surveys north of B6–B6A. These surveys helped to confirm that the crevasse fields shown 2 km apart on satellite imagery had actually merged to block the 2012 route. They also confirmed the presence of an extensive series of crevasses that did show up on the satellite imagery, which eliminated that terrain from further investigation by SCAT.

While *Yeti* conducted its B6 surveys, SCAT was able to prospect alternative route alignments to B9. It found a promising but narrow corridor between parallel crevasses. *Yeti* then conducted gridded surveys that helped to define the entrance and boundaries of this corridor and to ensure that no significant crevasses remained undiscovered between SCAT's manual surveys. This corridor became a key part of GrIT14's safe route.

Overall, *Yeti* conducted 23 autonomous GPR surveys covering 94 km of terrain while SCAT conducted independent surveys elsewhere. These surveys expanded SCAT's coverage and increased its understanding of the crevassed terrain in critical sections. The surveys also yielded a database containing hundreds of georeferenced crevasses to validate alternate remote-sensing platforms. We estimate that SCAT's time savings resulting from the *Yeti* surveys was nearly 6 days in total, based on the following breakdown:

- Northern B0 day-trip surveys—2 days
- Late-evening B5 crevasse-free route alignment—2 hr
- Grid surveys B6 to B6A—1 day
- B8 to B9 corridor entrance and boundary surveys—4 hr
- Repeated surveys to confirm safe corridors—2 days

Yeti's ability to conduct continuous, gridded surveys across closely spaced crevasses was particularly helpful to delineate safe corridors and to ground truth satellite imagery. In fact, it is probably not feasible or appropriate for SCAT to conduct systematic gridded surveys across crevasse fields. At each crevasse, the team would need to assess whether it was safe to cross

the snow bridge. This process entails stopping the vehicle, pausing the GPR, judging the snow bridge thickness and span from the radar data or manual snow probing, and holding a team discussion to decide whether to cross. Importantly, the GPR signature of a crevasse depends on vehicle approach angle and local snow conditions. The risk is always present that SCAT might miss a potentially dangerous crevasse on GPR. More commonly, SCAT encounters crevasses that it cannot safely cross and must therefore retreat, leaving terrain beyond such crevasses unexplored. *Yeti* is far better suited to the task of conducting systematic gridded surveys. Its low weight and ground pressure allow it to pass safely over bridged crevasses, and in the unlikely event that it should break through a snow bridge and be damaged, it can be repaired or replaced.

3.2 Lessons learned

The 2014 *Yeti* deployment was the first robotic effort directly to support operational crevasse detection in either Greenland or Antarctica. Previous deployments (Lever et al. 2013; Barna et al. 2015) provided important insight but did not include the intense schedule pressure to clear a safe route for an over-snow traverse. By comparison, manual GPR surveys to detect crevasses have been used for more than 20 years, and SCAT was especially efficient in this process. Consider SCAT's key personnel: Allan Delaney is arguably the world's leading GPR expert in operational crevasse detection, scientist Zoe Courville provided real-time second opinions on crevasse-signature interpretation, Robin Davies worked several seasons with SCAT as vehicle operator to learn the nuances and demands of the navigator's role, and mountaineer Galen Dossin had years of experience with operational crevasse surveys to judge and mitigate safety risks. Our field experience with this team provided several important lessons and identified readily achievable refinements to increase *Yeti's* operational efficiency.

The main inefficiency was the need to review GPR files manually to identify crevasse signatures. We reviewed these files each evening and then georeferenced the crevasse locations to include them in SCAT's master map. This delayed availability of the results by 1–2 hr. Machine-learning algorithms can identify crevasse signatures on GPR files during post-processing and thereby speed up the mapping process (Williams et al. 2012a, 2012b, 2014). Dartmouth, with CRREL encouragement and assistance, has developed these algorithms by using educational grants. Further research is needed to validate the algorithms against Greenland crevasse signatures, and the *Yeti* 2014 dataset is ideal for this purpose. Automated

crevasse detection would significantly speed up the availability of *Yeti* survey results for use by SCAT.

We have already overcome a second GPR-related inefficiency: the data-file limits of the radar controller. The SIR-3000 controller used initially in 2014 had a file limit of 60 MB, which required stopping *Yeti* and saving the radar file every 45 min. For the last four surveys, we swapped the SIR-3000 for the more capable SIR-30; its 4 GB file limit permits 40 hr of surveys using the same radar settings. We packaged the SIR-30 on a sled with its own battery pack, and recent experience with the same package in Antarctica (Arcone et al. 2016) showed approximately 20 hr of radar-battery endurance. Even CRREL's less-expensive SIR-4000 (the SIR-3000's commercial replacement with a 2 GB file limit) could achieve 20 hr of continuous robotic surveys. Therefore, using these new options, radar file capacity is no longer a limit for *Yeti* surveys.

Yeti itself performed extremely reliably—it was ready to run every time we turned it on. This would be exceptional performance for any polar vehicle and speaks well of its design and maintenance. By contrast, the commercially produced PistenBully frequently experienced electrical and heater problems that delayed or impeded its operation.

Yeti did experience immobilization on two occasions: once executing an uphill turn in soft snow and once travelling across fresh, deep ruts made by the PistenBully. These particular ruts were deep because the tight corridor demanded that the PistenBully execute a pivot turn. On numerous other occasions, *Yeti* crossed PistenBully and Tucker ruts without difficulty. Fortunately, immobilizations in vehicle ruts along a crevasse-free corridor allow for safe, easy recovery and restart of *Yeti*. Immobilizations in remote terrain are more problematic and require that SCAT survey out to the rover to ensure safe recovery. Despite the presence of softer snow in Greenland than in Antarctica, *Yeti* immobilizations in remote terrain are rare, and its reliable waypoint navigation ensures that these occur along the programmed course, minimizing search effort. Nevertheless, the addition of a satellite-linked GPS tracker would reduce anxiety over the location of the rover if it is out of radio contact and does not return on schedule. A tracker would also provide continuous location data when topography limits *Yeti*'s radio range (typically several kilometers).

During the 2014 deployment, *Yeti's* 4 hr battery endurance was not a serious limit. However, the SIR-30 can operate unattended for up to 20 hr. Because the SIR-30 resides on a sled, it frees up space in *Yeti's* battery bay to increase the rover's endurance to 6–8 hr. Batteries add weight, and 6–8 hr GPR files might be hard to process efficiently. Still, this option is worth evaluating because it would extend *Yeti's* range of independent operation and allow more flexible tasking by SCAT.

We planned and executed *Yeti's* surveys on demand from SCAT, using the PistenBully to deploy and recover the rover. Whenever SCAT was also conducting surveys, safe protocol required that our PistenBully and mountaineer follow closely behind it to serve as a safety backup. This often meant leaving the course vicinity and recovering *Yeti* after it completed its survey. We embraced this functional mode to demonstrate that *Yeti's* operation could mesh efficiently with SCAT's. We had only one instance where this dual purposing of resources caused a problem: on 5 March 2014, *Yeti's* SIR-3000 GPR lost battery power before we could return and save the radar file. Again, we eliminate this problem by using the long-endurance SIR-30 or SIR-4000 for future *Yeti* GPR surveys.

3.3 Autonomous survey costs

We aimed to minimize direct costs for *Yeti* to support SCAT (\$46,500) by using personnel already deployed to support SCAT and GrIT. In addition, CRREL provided all of the radar equipment at no cost, except to prepare and ship it to Greenland. This in-kind support is likely to continue for the foreseeable future as we refine and validate autonomous GPR surveys and crevasse detection, and it represents a significant contribution: the SIR-30 and SIR-4000 radar controllers cost \$25,000 and \$17,000, respectively, and antennas, cables, and batteries add another \$5,000. Note also that Dartmouth provided *Yeti* and its support equipment at no cost, except for CRREL to prepare and ship it to Greenland. CRREL is currently building a duplicate of *Yeti* for the U.S. Antarctic Program, a cost of \$144,000. So again, the support-in-kind value of *Yeti* to SCAT was significant.

CRREL and Dartmouth are collaborating to advance *Yeti's* capabilities independent of GrIT/SCAT. Under NSF science grants 1246400 and 1245915, *Yeti* recently conducted over 600 km of autonomous GPR surveys across the crevasse-ridden McMurdo Shear Zone in Antarctica in October–November 2014 (Arcone et al. 2016). Both the rover and the SIR-

30 radar performed flawlessly. To improve efficiency, we developed simple algorithms to generate survey courses and to map the resulting rover tracks. Current research at Dartmouth will validate crevasse-detection algorithms by using the resulting dataset of thousands of crevasse crossings. It will also seek to implement onboard the rover the updated algorithms to identify crevasses in real time. If successful, this work would enable several key advances for operational crevasse detection: (a) real-time mapping of crevasse locations relayed from the rover to its base station, (b) zig-zag survey courses where the rover turns at boundary crevasses and thereby mimics manual surveys to identify safe lanes, and (c) real-time crevasse warning to aid manual GPR interpretation and to reduce operator stress.

4 Conclusions and Recommendations

Overall, *Yeti's* autonomous GPR surveys contributed to SCAT's successful efforts to find and verify a safe route for GrIT in 2014. The rover was operationally reliable, and the survey results were incorporated into the master map for SCAT's route planning and assessment. Direct costs were low: Dartmouth and CRREL contributed the rover and radar equipment, and *Yeti's* deployment leveraged SCAT's PistenBully support vehicle, second mountaineer, and second GPR operator. *Yeti's* shortcomings derived mainly from the newness of the technology mode—these were the first autonomous surveys to support operational crevasse detection directly.

Given recent trends, crevasse conditions along GrIT's route are likely to become even more complex. This will place exceptional demands on the skill and efficiency of SCAT to prospect and verify a safe route. Therefore, we recommend the following improvements to make *Yeti* fully operational as a time- and cost-saving resource for SCAT:

- Implement and verify Dartmouth's crevasse-detection algorithms for operational use in Greenland by using *Yeti's* extensive 2014 dataset as validation.
- Boost *Yeti's* endurance (battery capacity) to 6–8 hr and add a GPS tracker to extend its range of independent operation.
- Deploy *Yeti* with the SIR-30 and crevasse-detecting algorithms on SCAT in 2016, and assess their impact on survey efficiency.

With these improvements, *Yeti* can become an essential member of SCAT, allowing for faster and safer crevasse detection and reduced time, cost, and stress for SCAT to verify a safe route for GrIT.

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14. ABSTRACT
The National Science Foundation operates the Greenland Inland Traverse (GrIT) to resupply Summit Station, which is situated at the peak of the Greenland ice cap. Prior to its springtime departure from Thule Air Base in northwest Greenland, GrIT's Strategic Crevasse Avoidance Team (SCAT) conducts ground-penetrating-radar (GPR) surveys along the first 100 km of the route to chart a safe course around subsurface crevasses that could jeopardize the safety of vehicles and personnel. We deployed the polar rover *Yeti* during 2014 to supplement SCAT's survey capabilities. *Yeti* executed 23 autonomous GPR surveys, covering 94 km of terrain. The resulting data allowed us to map hundreds of subsurface crevasses and contributed to SCAT's successful charting of a safe route for GrIT. These were the first robotic surveys that directly supported concurrent manual crevasse surveys. This report describes the techniques used during *Yeti's* 2014 deployment, the survey results obtained, the main contributions of *Yeti* to SCAT's efforts, and recommendations to improve the efficiency of robotic crevasse surveys to aid manual ones.

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