ERDC/CRREL TR-15-10

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# Remediation of Old South Pole Station Using Autonomous Data Collection and Remote Assessment of Ground-Penetrating Radar

Lynette Barna, James Lever, and Allan Delaney

July 2015

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# Remediation of Old South Pole Station Using Autonomous Data Collection and Remote Assessment of Ground-Penetrating Radar

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Final Report



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# Abstract

This report describes a ground-penetrating-radar (GPR) survey assessing the effectiveness of blasting subsurface hazards at the original South Pole Station. Hidden under layers of accumulated snow, false attic structures ("top hats") were built on top of the original buildings to displace the increasing snow depth. By causing an alteration in the snow structure through enhanced metamorphism, the presence of these structures and heat from the buildings reduced the bearing capacity of the overlying snow to support surface-based heavy vehicle.

Blasting was an effective method to mitigate the subsurface safety risks posed to personnel and equipment operating in the area. The resulting blast crater naturally filled with drift snow. An autonomous polar rover was deployed and successfully conducted a post-blast GPR survey operating at ambient temperatures of −22°F or lower. Expert review of the GPR data confirmed that the targeted structures within the crater were effectively demolished. Data collected by the rover revealed two sites beyond the crater perimeter, yet within the survey area, that posed a risk to heavy vehicles. A mitigation effort included these two areas. Data collection with an autonomous rover and off-site expert data review proved to be effective tools for use at South Pole.

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# Preface

This investigation was funded by the National Science Foundation (NSF), Division of Polar Programs (PLR), Antarctic Infrastructure and Logistics, under Engineering for Polar Operations, Logistics, and Research (EPOLAR) EP-ANT-12-41, “Old South Pole Station.” The technical monitor was George Blaisdell, Chief Program Manager, NSF-PLR, U.S. Antarctic Program.

This report was prepared by Lynette A. Barna and Dr. James H. Lever (Force Projection and Sustainment Branch, Dr. Loren Wehmeyer, Acting Chief) of the U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL), and Alan Delaney, contractor, of Alpine, TX. At the time of publication, Dr. Loren Wehmeyer was Chief of the Research and Engineering Division. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Robert Davis.

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LTC John T. Tucker III was the Acting Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

# Acronyms and Abbreviations

| | |
|---|---|
| ASC | Antarctic Support Contract |
| 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 |
| GSSI | Geophysical Survey Systems, Inc. |
| IGY | International Geophysical Year |
| NSF | National Science Foundation |
| PLR | Division of Polar Programs |
| RPSC | Raytheon Polar Services Contract |

# Unit Conversion Factors

| Multiply | By | To Obtain |
|---|---|---|
| cubic feet | 0.02831685 | cubic meters |
| degrees (angle) | 0.01745329 | radians |
| degrees Fahrenheit | (F-32)/1.8 | degrees Celsius |
| feet | 0.3048 | meters |
| inches | 0.0254 | meters |
| pounds (force) per square inch | 6.894757 | kilopascals |
| pounds (mass) | 0.45359237 | kilograms |

# Executive Summary

In December 2010, the first phase to remediate the site of the original South Pole Station (Old Pole) was completed using explosives that demolished the buried structures within the principal complex. During the time Old Pole was in operation, blowing and drifting snow accumulated around the surface-constructed buildings, eventually burying them. In an attempt to displace the accumulating snow on the rooftops, false attics, or "top hats," were constructed. Today, the buildings are covered by approximately 30 ft of snow. These top hats posed safety risks as the overlying snow layers had insufficient strength to support vehicle traffic. Indeed, two unintended vehicle penetrations in early 2010 confirmed this concern. Blasting represented an effective method to implode the below-grade structures to mitigate such risks without affecting ongoing science operations.

Prior to blasting, ground-penetrating-radar (GPR) surveys that applied conventional practices and equipment for crevasse detection located and defined the buried structures (Barna et al. 2015). The extent and depths of these buried buildings was needed to determine where to set the charges. The subsequent three-blast series produced a crater approximately 325 ft long, 80 ft wide, and 15 ft deep. Blowing snow during the ensuing winter naturally filled the crater up to the existing grade level.

In December 2011, CRREL engineers conducted a follow-up GPR survey over the footprint of the blasted area, the primary goals being to verify the collapse of the top hat structures built on top of the original T-5 buildings and to identify any additional subsurface hazards that posed a risk within the immediate vicinity of Old Pole. Results from the survey were used to refine the next steps in the remediation plan. We executed the survey using an autonomous polar rover, Yeti, to collect the GPR data without risk to personnel. The GPR data and the Global Positioning System (GPS) track data were transmitted to the continental U.S. for expert review and evaluation. Using an autonomous rover and off-site data review were both new approaches to GPR surveys, with wide-ranging applicability within the U.S. Antarctic Program, and we sought to evaluate their effectiveness as secondary goals of this study.

Using GPS waypoint navigation, Yeti executed closely spaced autonomous survey grids over the test site on three successive days for the follow-up survey. The rectangular test area, which included the blast crater, measured 445 × 200 ft. Two survey grids crossed the short axis of the site and one crossed the long axis. Ambient air temperatures ranged from −20°F to −27°F, and no immobilizations occurred. GPS position accuracy was adequate for these surveys, and Yeti had no obvious resolution issues navigating in close proximity (within tens of meters) of 90° south. The consistent speed of the rover produced radar data of high quality and clarity, aiding the resolution of subsurface features for interpretation, and transmission rates from the station were sufficiently fast to allow daily off-site review. Daily phone conversations confirmed data quality and improved the remote reviewer's understanding of survey operations.

Based on these surveys, it appeared that blasting effectively demolished all structures within the crater area, designated as Area 1, and no hazards to vehicle traffic remained within that area. Two additional areas outside the perimeter of the crater posed hazards for equipment and personnel, calling for further attention. Two buildings (A15 and A21) along the eastern perimeter of the site, identified as Area 2, outside of the blast crater, appeared to be intact at depths approximately 10–15 ft below the surface. Strong radar reflections observed in the GPR data near the location of Building A10 suggested an intact building 11–13 ft below the surface. The dimensions of this area were 20 × 20 ft, and it was designated as Area 3.

In January 2012, the National Science Foundation approved the remediation plan. The primary contractor, Raytheon Polar Services Contract, carried out the remediation tasks during the 2012–2013 summer season. Area 1 was backfilled using bulldozers in a 3-pass progression pushing snow followed by leveling and grading. Areas 2 and 3 were excavated to expose the structures and backfilled with snow to fill as much of the void as possible. Excavation in Area 3 revealed an intact metal-roof structure covering an interior building. To mitigate the subsurface hazards in Area 3, blasting was used during the 2013–2014 austral summer. The resulting crater was allowed to naturally fill with drift snow.

The GPR data revealed a weak interface, or crack, along the northern (windward) margin of the original blast crater between the vertical wall and the drift snow in Area 1. We estimated the crack width to be too narrow to threaten vehicle operations; this posed a hazard to pedestrian foot traffic. On-site personnel probed along the interface using hand tools to determine the depth and extent. Personnel followed safety procedures when conducting the subsurface investigation. As planned, backfilling using heavy equipment closed the cracks to sufficient depth to eliminate the hazard to personnel.

Consistent with GPR survey results from 2010, the Emergency Generator Vault (Building A20) located in the southwestern corner of the survey area did not indicate any subsurface hazards.

Numerous survey transects across the area of Building A25 (Supply/Parking and Berthing) indicated that the building had collapsed in the blast and that the top of the building was approximately 30 ft below snow grade.

Collecting the survey data using the autonomous rover and off-site expert data review proved to be effective tools to conduct the GPR survey and assess the data in near real time. Simple improvements for future autonomous surveys include use of a differential GPS base station, minor algorithm changes to improve navigation accuracy, and an overlay of GPS position data directly onto GPR data files to improve synchronization. Additionally, the off-site reviewer should be provided with the same geographic information system used on-site to map rover survey lines.

Dr. James Lever (CRREL) and Martin Lewis (Raytheon Polar Services) pictured at the geographic South Pole with the polar rover, Yeti. Yeti was the first vehicle to function autonomously at the South Pole.

# 1 Old South Pole Station

## 1.1 Background

During the 2010–2011 austral summer, to prepare the site for blasting remediation, a team of CRREL engineers conducted an initial ground-penetrating-radar (GPR) survey at Old Pole to locate naturally buried manmade buildings covered by approximately 30 ft of snow. This report provides a brief overview of the initial GPR study; additional details are provided in Barna et al. (2015).

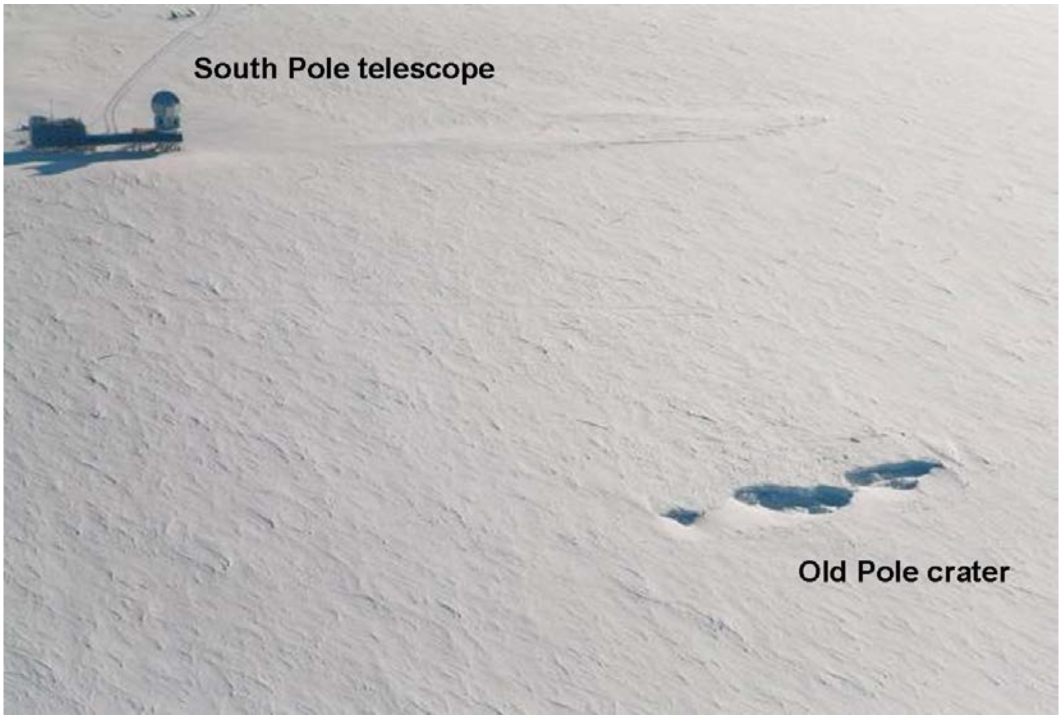
The original South Pole Station was constructed in 1956–1957 by the U.S. Navy in support of the scientific investigation activities for the International Geophysical Year (IGY). Blowing and drifting snow eventually buried the entire South Pole complex though the station continued to operate until it was abandoned in the 1970s for the new South Pole Station, a surface-based domed structure. The National Science Foundation (NSF) and their contractor Raytheon Polar Services Contract (RPSC) identified a group of nine buildings located within the primary complex of the original Old Pole as posing the greatest hazard to personnel and equipment. False attic structures, called “top hats,” had been constructed on top of the original single-story, pre-fabricated, T-5 buildings to displace accumulating snow during the station’s operational years. In some cases, the top hat structures were stacked so that there were two layers of top hats.

As a material, snow has a poor bearing capacity; however, continuous, thick, homogeneous layers of snow are capable of supporting high ground pressure loads, such as heavy equipment and pedestrian traffic. Following closure of the original South Pole Station, the top hat structures were never mitigated and were increasingly covered with blowing and drifting snow. Their presence created dangerous subsurface voids, weakening the overlying snow layers by altering the snow structure through increased snow metamorphism driven by heat stored in the buried structures. The initial GPR survey of the area used manual methods and was conducted using the equipment configuration and analysis techniques typical for crevasse detection. The GPR radar unit was attached to a boom on the front of a manually driven tracked vehicle that pushed the radar unit, keeping it in contact with the snow surface. As the GPR data was collected, the data were continuously read in real-time by skilled operators looking for immediate dangerous subsurface hazards. When the GPR operator detected a hazard, the vehicle would have time to stop before traveling over an unsafe feature. During post-processing, the GPR data were used to identify the locations and depths of each of the buried buildings.

As NSF, under recommendation from RPSC, chose blasting to mitigate the nine buried buildings in the primary complex of Old Pole, once the building locations and depths were known, the information was transferred to the snow surface. This demarcated each building location and delineated where to drill the holes into the snow to place the explosives to implode these buried structures (Barna et al. 2015). The dimensions of the resulting blast crater measured approximately 325 ft long × 80 ft wide × 15 ft deep. Based on the GPR data, buried structures located outside the perimeter of the primary complex were not considered hazardous.

A post-blast GPR survey was not conducted during the remainder of the 2010–2011 austral summer season as access into the crater was deemed too hazardous. Accumulating and blowing snow naturally filled the crater. Two months after the blasting operations, the crater was nearly entirely filled (Figure 1). NSF and RPSC did need to evaluate the effectiveness of blasting to demolish the top hats. The risk involved in collecting GPR data with a manual equipment configuration similar to the initial survey was very high given the unknown stability of the drift snow, especially along the northern (windward) edge, coupled with the potential existence of subsurface voids as a result of blasting. These risks made entering the drifted crater with personnel and equipment unsafe. In addition to assessing the effectiveness of the blasting, information obtained from GPR surveys would be needed to refine the follow on tasks to harden the Old Pole area. Therefore, the evaluation required a different approach.

Figure 1. An aerial view of the crater at Old South Pole taken 3 February 2011, two months after the conclusion of blasting activities (modified from RPSC internal communication).




## 1.2 Problem

RPSC used blasting to implode the top hat structures constructed on the original buildings within the main complex of Old Pole. Following these mitigation activities, it was necessary to evaluate the effectiveness of the blasting and the resulting subsurface material density. While GPR was the preferred method to collect data on the subsurface conditions, the risk was too high to allow personnel and equipment to travel over the crater area.

## 1.3 Project objective

To minimize the exposure of personnel and equipment to potential subsurface hazards in the area of the drifted-in blast crater, we used an autonomous polar rover to conduct a detailed GPR survey. Once we identified hazardous areas, conventional methods of characterization were used following appropriate safety procedures.

## 1.4 Technical approach

We visited South Pole Station from 29 November to 10 December 2011. Using an autonomous polar rover (Yeti) during a 3-day period, we conducted the GPR survey over the inclusive crater area plus a 60 ft buffer zone. We transmitted the GPR data back to the U.S. for review by a subject-matter expert familiar with the site. The near real-time review and feedback of the GPR survey data, along with communications via electronic and voice formats during times of satellite coverage, provided feedback to maintain an efficient tempo to collect and evaluate the data. RPSC provided valuable project support during this fieldwork.

## 1.5 Project scope

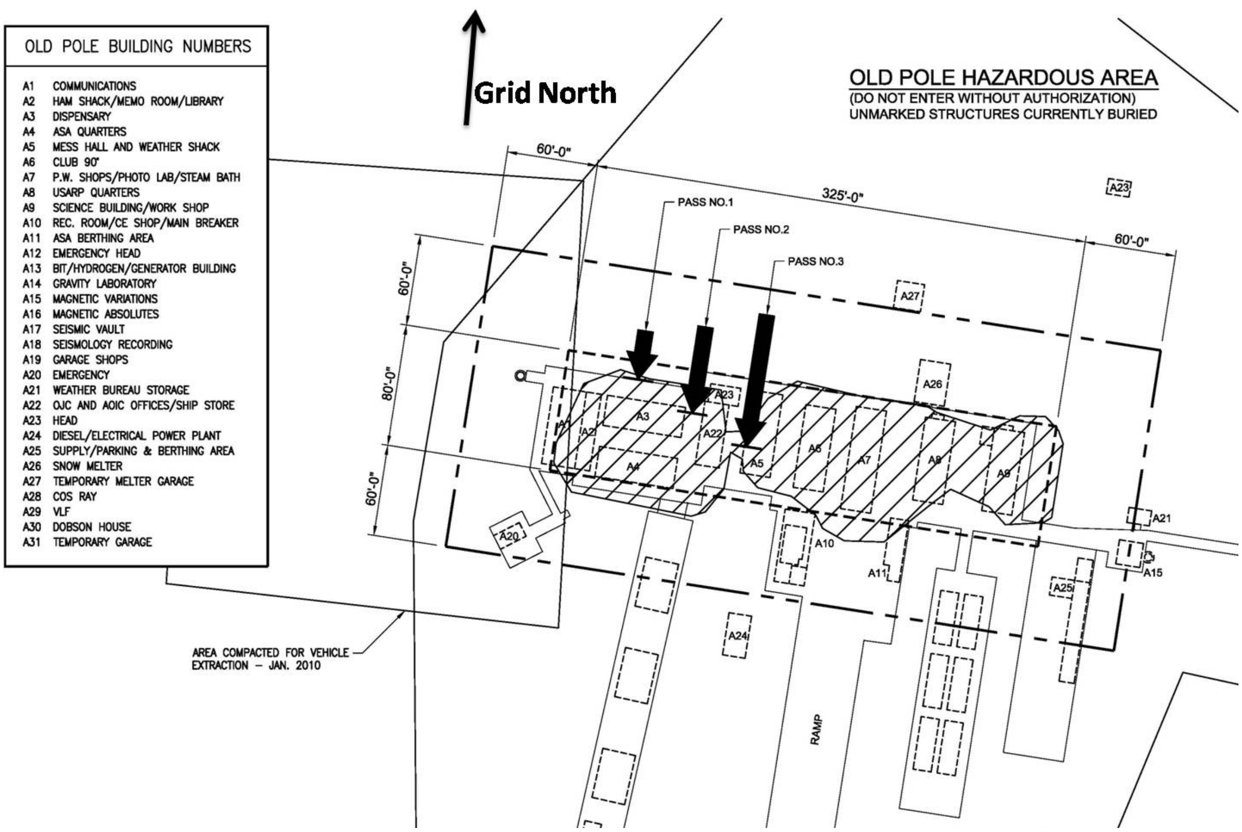
The test area for the GPR survey focused on the footprint containing the blast crater plus a surrounding 60 ft perimeter. In the post-blast GPR dataset, we disregarded reflections from sources outside of the blast area, provided they were consistent with the interpretation of reflections from the 2010–2011 survey and were not hazardous. In contrast to the initial GPR survey using a radar unit mounted in front of a tracked vehicle to identify and to locate the intact buried structures, here the radar unit was towed behind the polar rover. Familiarity with the 2010–2011 GPR dataset and the Old Pole station layout greatly facilitated the review process (Barna et al. 2015). Existing knowledge of and experience with crevasse detection during overland traverses also played an important role in reviewing the GPR data profiles. Results from the GPR survey were used to refine the follow-on tasks in the remediation plan. Three areas were identified for remediation, of which two were completed during the 2011–2012 season. Blasting was again used during the 2013–2014 summer season to implode the identified buried structure within the third area.

# 2 Field Testing and Data Collection

## 2.1 Old South Pole test area and layout

The rectangular-shaped test area was 445 ft long × 200 ft wide (Figure 2). The drifted-in crater was centrally located within the test area and was surrounded by a 60 ft buffer zone established for the proposed backfilling procedure. The RPSC survey team flagged the test area per RPSC's FY2012 Summer Work Plan (RPSC, unpublished report, 2011). We focused the autonomous GPR survey within the established perimeter of the test area. For safety reasons and because the subsurface conditions were unknown, personnel were restricted from entering into the test area beyond the flagged perimeter.

Figure 2. The Old South Pole test-area layout showing the locations of imploded buildings and the border of the blast crater. The perimeter was marked with red flags. (Image by RPSC.)



## 2.2 Autonomous ground-penetrating-radar survey

### 2.2.1 Autonomous polar rover

The autonomous rover, Yeti, was specifically designed to conduct GPR surveys in challenging polar environments and was developed through a partnership between Dartmouth College and the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). Yeti has been used successfully in the harsh Arctic and Antarctic environments to detect crevasses for overland traverses, withstanding air temperatures of −22°F. Figure 3 is a photograph of Yeti supporting the South Pole traverse during a GPR survey in the McMurdo shear zone crossing. With its smaller footprint and tighter turning radius, the robot is capable of collecting high quality GPR data at closer spacing compared to the more conventional approach of a small-tracked, over-snow vehicle outfitted with a forward-extending boom containing the radar antenna.

Figure 3. The Yeti rover deployed to the McMurdo shear zone crossing to support the South Pole Traverse (October 2010). In the background is a tracked over-snow vehicle, one type of vehicle used to conduct manual GPR surveys, equipped with identical instrumentation as the rover.

Yeti is battery powered, weighs approximately 160 lb, and exerts a low ground pressure at approximately 2 psi through 20 in. pneumatic ATV tires. It has a small footprint, 12 in. of ground clearance, and a central chassis pivot to maintain four-wheel contact over rough terrain. With 4-

wheel drive, it has displayed excellent mobility over polar snow during three deployments in Antarctica and two in Greenland. Autonomous navigation is via Global Positioning System (GPS) waypoints following a predefined survey grid loaded into the robot, or manual control is through a 2.4 GHz radio link. A 400 MHz GPR antenna is towed behind the robot in an air cushion and is the same equipment commonly used to conduct manual GPR surveys (Figure 4). A Geophysical Survey Systems, Inc. (GSSI), SIR3000 radar controller is on board the rover. The forward compartment on the rover houses the control electronics while the lithium-ion batteries and radar controller are located in an insulated rear compartment to keep the batteries warm for sufficient run time.

Figure 4. The Yeti rover conducting an autonomous GPR survey at the Old Pole site. To maintain close contact between the radar antenna unit and the snow surface and to protect the unit from severe vibration, the GPR 400 MHz transducer is mounted within an inflated inner tube and towed behind the rover. The GPR control unit is contained in the left compartment on the rover, between the wheels. In the background is the Amundsen-Scott South Pole Station in close proximity to the geographic South Pole.

### 2.2.2 Global positioning system

GPS coverage was quite good at South Pole with reception of ten to twelve satellite signals consistently supplying location information. During data collection, the rover's onboard data collection system recorded GPS readings at 1 sec intervals. These data were mapped over the surveyed Old Pole site to see Yeti's tracks. Position accuracy ranged from 2 to 10 ft. The autonomous navigation worked quite well, even at close proximity to the geographic South Pole (Figure 4). The rover experienced no operational issues at air temperatures ranging from −20°F to −27°F during the survey.

When not in use, Yeti was sheltered but remained cold soaked at similar sub-freezing temperatures.

#### 2.2.3 Ground-penetrating-radar survey

Prior to completing the GPR survey over the test area, we confirmed the rover's operation and data collection through an initial quality control test. We operated the rover at a speed of 2.7 mph, a collection speed similar to that of the small-tracked, over-snow vehicle used in the GPR survey the prior year. Radar data were collected at a rate of 24 scans per second by operating the robot in manual mode. Using a secure Army file transfer site, we transferred the data files to the U.S. for review. The review confirmed the high quality of the radar data as a result of the rover's slow constant speed providing data consistency and clarity. Following this confirmation test, the designated test area of Old South Pole was surveyed over a three-day period. The GPS waypoints were loaded into the rover and Yeti traversed the designated test area autonomously. We transferred these radar data files off continent for review and interpretation. We also used photographs, video, and field notes to document the survey.

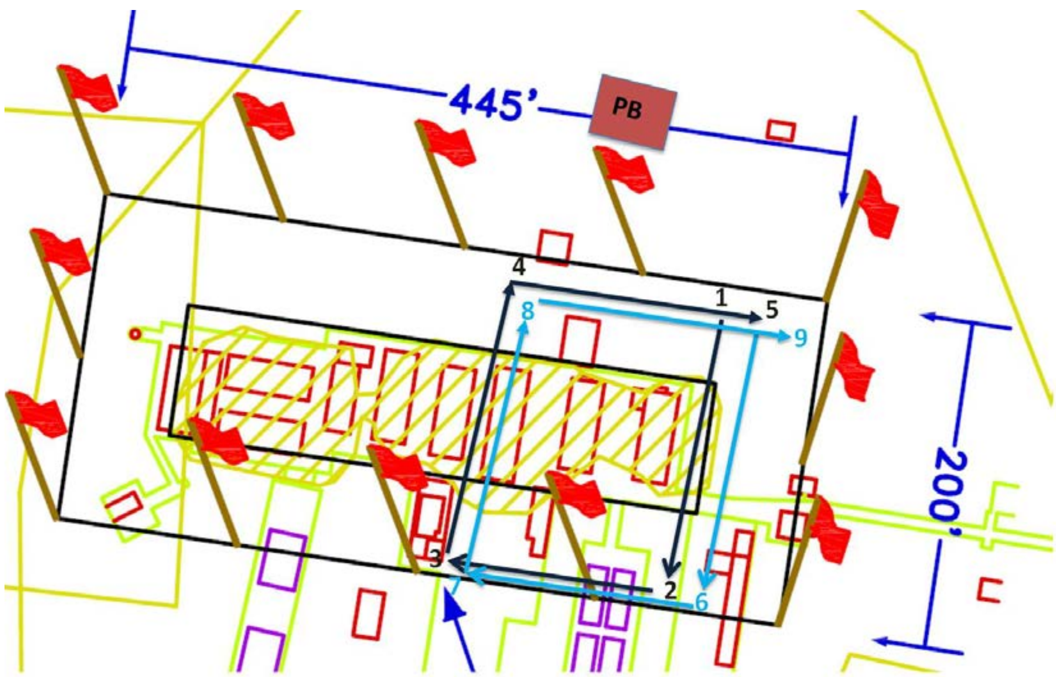
#### 2.2.4 Radar files

In all, a total of 396 MB of radar and data files (including the quality control testing) were transferred back to the U.S. for review and analysis. Following data collection, we performed a cursory review of the radar data before uploading them. Daily internet access at South Pole is available during a satellite pass (totaling approximately nine hours per day). Depending on satellite availability, the daily satellite access windows shifts slightly. We planned the data collection periods to allow adequate time to transfer the files before the scheduled end of a satellite pass and to review the data back in the U.S. by our subject matter expert (keeping in mind that local time at the South Pole follows New Zealand and is 18 hr ahead of the U.S. East Coast). The typical transfer rate through the satellite link was 1 MB/min. Daily phone calls and electronic communication provided near real-time assessment of the radar data, set the schedule for the next survey, and determined any areas requiring re-surveying.

#### 2.2.5 Establishing the survey grid

The survey grid was a series of waypoints based on the surveyed coordinates of the corners of the test area. The rover completed grids in two directions: an initial grid oriented north–south and a grid oriented east–west perpendicular to the first grid. There were a total of three grids: the east–west grid and the north–south grid, which was divided into two (east and west). The grid pattern resembled a 4-point Zamboni configuration. Figure 5 illustrates the pattern used on the eastern end of the test area. At each corner point, Yeti paused for 4 seconds before turning to proceed to the next point. In the GPR data file, the pause was recognizable indicating the location of the rover. A single pass consisted of the four corner points. Once Yeti completed a pass, the rover indexed over approximately 8 ft and began the next pass. As a quality control measure, the CRREL team in the field manually recorded the time and location of each pause. The rover completed each survey grid in approximately 1.5 to 2 hr over a three-day period (6–8 December 2011).

Figure 5. A sketch showing the north–south survey grid used on the eastern side of the Old South Pole test area. A similar grid was used on the west side. The small tracked vehicle (labeled "PB" in the sketch) was positioned on the north side outside the perimeter line for visibility to the rover and good signal connection.




Yeti completed the east–west GPR survey grid (along the long side of the test area) direction in a similar fashion. Figure 6 shows the survey pattern.

The GPS tracks from the autonomous surveys were overlaid onto a map of Old South Pole. Figure 7 indicates the path of the rover during the surveys and verifies the complete survey coverage. The wide turns at the beginning of each transect were used as a precaution against breaking traction as the rover turned in the soft snow.

Figure 6. A sketch of east–west survey grid. The small tracked vehicle (labeled as "PB" in the sketch) was positioned on the western side of the perimeter line.

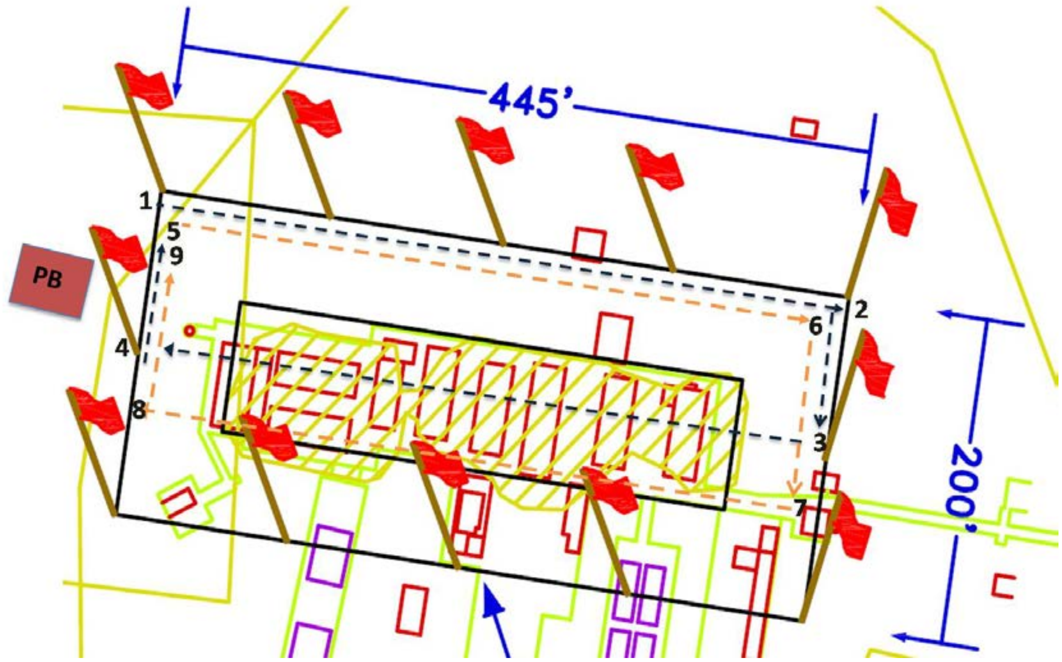
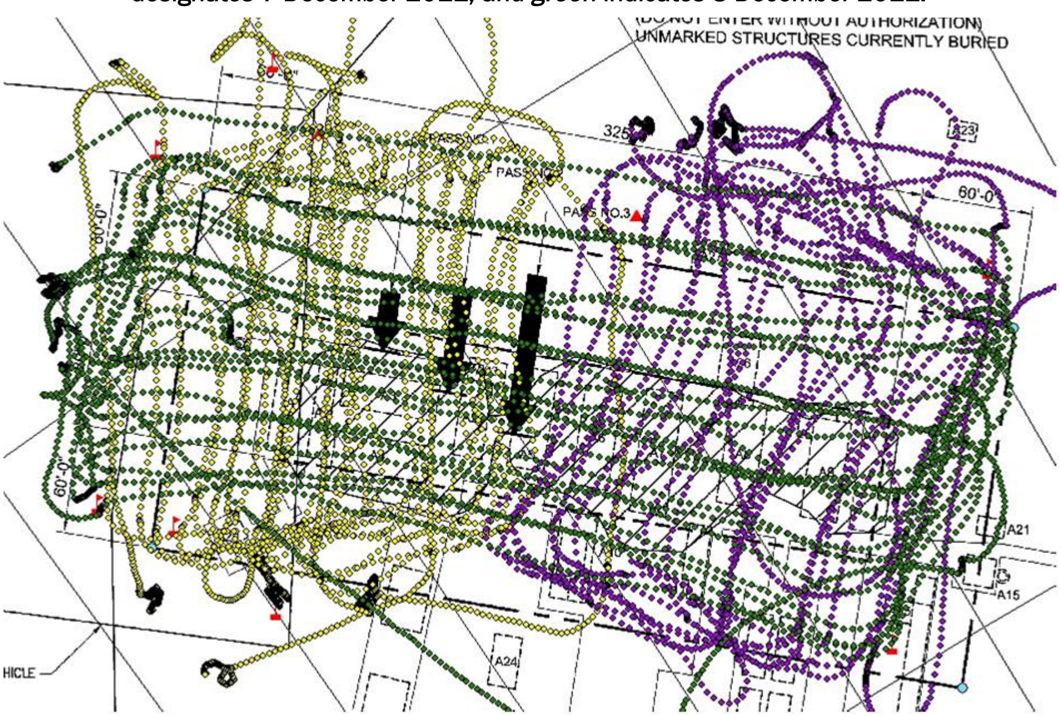


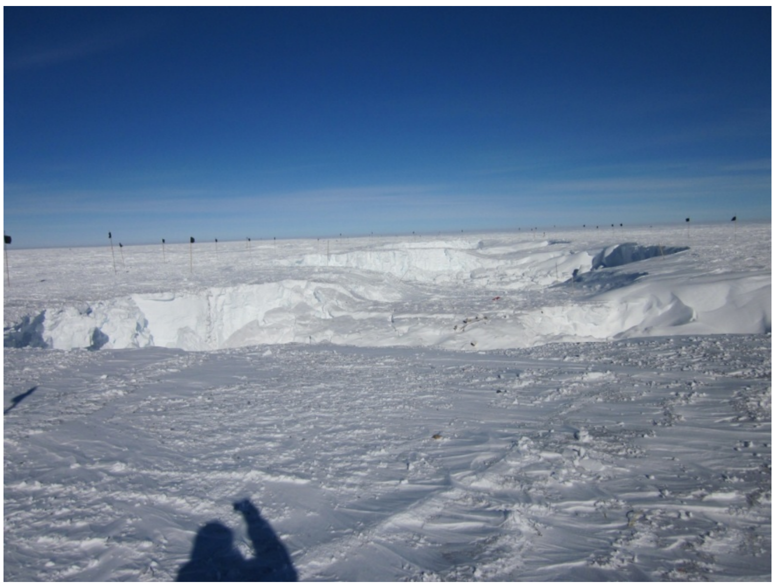

Figure 7. Yeti's position as indicated by 1 sec GPS tracking during three autonomous surveys over Old South Pole. *Yellow* indicates the survey conducted on 6 December 2011, *purple* designates 7 December 2011, and *green* indicates 8 December 2011.



## 2.3 Subsurface investigation

The displaced material from each blast collected in a mound along the crater's central horizontal axis (Figure 8). The drift snow filled the crater after blasting and created localized cornices on the crater's windward side, creating hazardous conditions, particularly at the vertical interface where drift snow often does not adhere well to the crater wall. Snow conditions within the crater were expected to be highly variable with some locations being more densely compacted as a result of the displaced debris.

Figure 8. A view looking west of the cratered area of Old South Pole after blasting was completed. Taken 10 December 2011, this illustrates the debris mounds along the center of the crater.



Following safety protocols, including using harnesses and ropes, RPSC personnel conducted a subsurface investigation along the crater's perimeter and interior. They used hand tools and poles (Figure 9) to probe the upper 6–8 ft below the snow surface and determined the presence of small, shallow subsurface voids along the interface between the crater wall and the drift snow, which they then exposed. Additionally, at two locations they collected cores using a 4 in. diameter fiberglass coring auger to obtain a snow density profile with depth.

Figure 9. RPSC personnel used hand tools to determine the depth and extent of small subsurface voids. (Photo by RPSC.)

# 3 Site Assessment Results

## 3.1 GPR data

The subject matter expert in the U.S. reviewed the GPR data files to determine the effectiveness of the blasting activities during the 2010–2011 austral summer and to identify whether any potential subsurface hazards remained prior to the planned backfilling activities. Familiarity with the 2010–2011 GPR dataset and the Old Pole station layout greatly facilitated the review process for the U.S. specialist. Knowledge and experience used in crevasse detection during overland traverses also played an important role in reviewing the GPR data (Arcone and Delaney 2000; Blaisdell et al. 1997; Delaney and Arcone 2005; Delaney et al. 2004, 1996; Taurisano et al. 2006).

The 2010–2011 radar survey and blasting operations focused on locating and demolishing the top hats and their attendant buildings as these posed the greatest hazard to both vehicle and foot traffic. Review of the 2011–2012 data thus initially focused on the in-filled blast crater to ensure that these structures were indeed demolished. We then more closely examined data from survey lines across the 60 ft wide buffer areas to assess whether structures outside the margin of the blast area could produce concealed hazards. We found the following:

- The 2010 blasting operations successfully imploded all of the buried structures located within the crater area. No hazards remain from the top hat structures and no other voids posing threats to vehicles remain within the blasted area.

- Two buildings (A15 and A21, Figure 2) at the eastern perimeter of the site, outside of the blast crater, appeared to be intact at depths approximately 10–15 ft below the snow surface. Figures 10 and 11 show typical radar sequences across this area along the north–south (Figure 10) and the east–west (Figure 11) directions. These structures could pose hazards to vehicles. We recommend that this area be flagged off and that heavy equipment be restricted from entering until further remediation. Both of these structures were outside the 2010 blasting operations boundary and at the time were not considered to pose a hazard.

Figure 10. A typical radar reflection oriented north–south across buildings A15 and A21 along the eastern boundary of the test area. The specialist in the U.S. interpreted the subsurface features and the estimated depths below the snow surface (vertical axis). The vertical axis is the radar signal's vertical travel time; the horizontal axis is a linear distance.

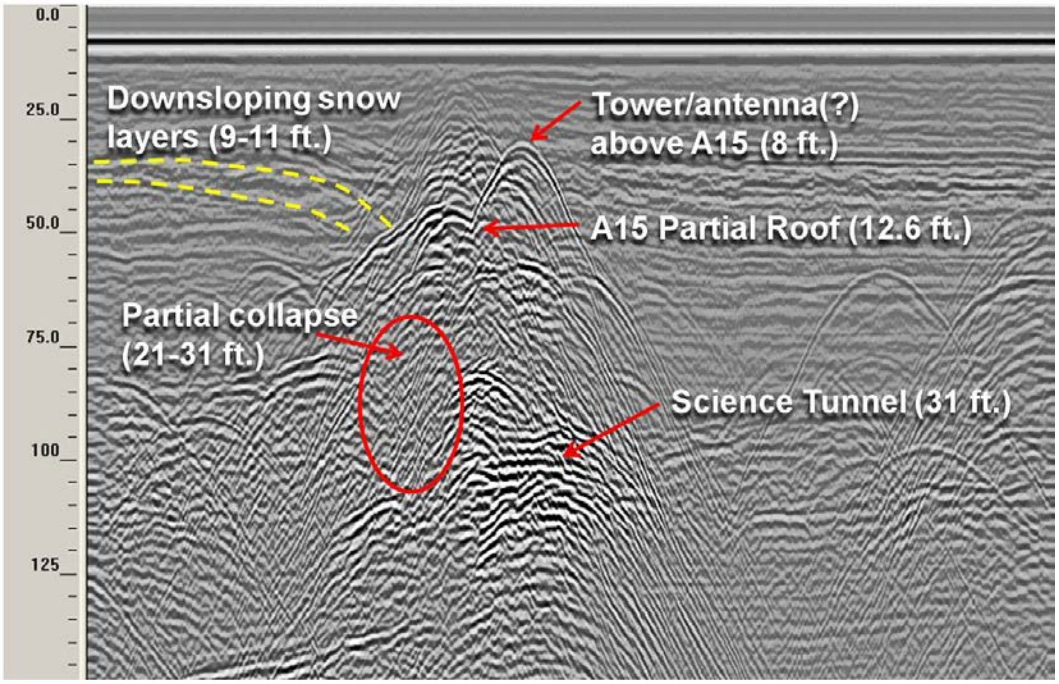
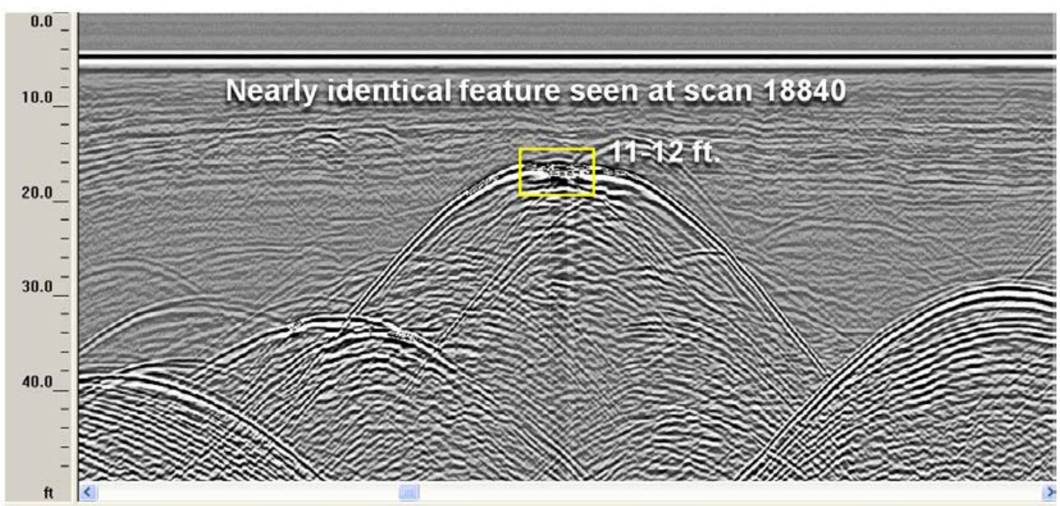
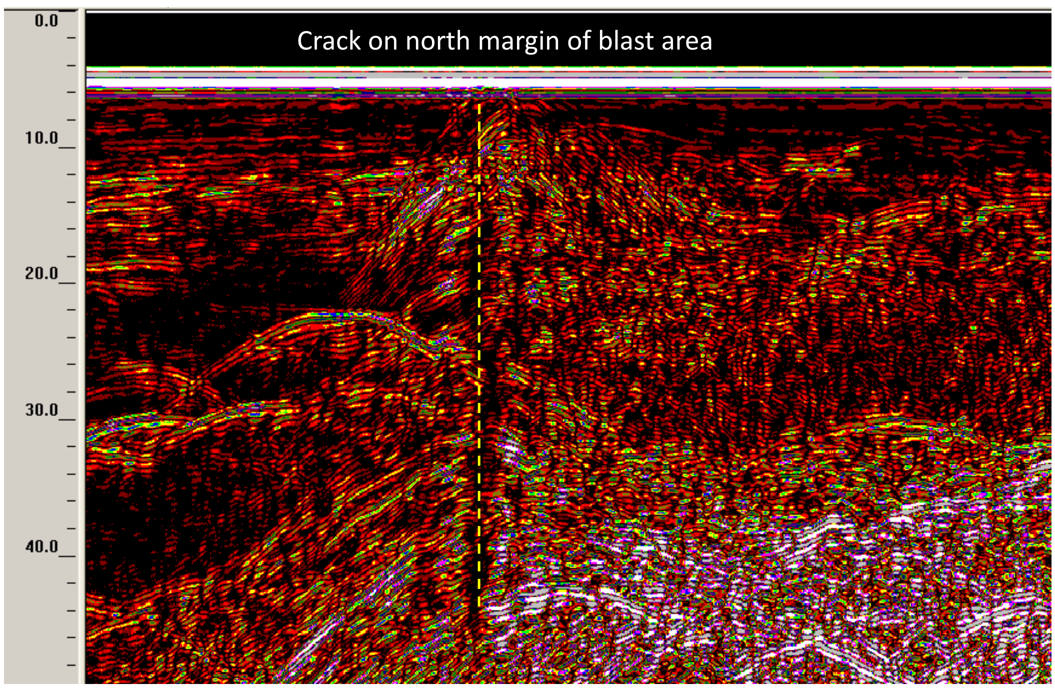



Figure 11. A radar sequence oriented east–west near building A10 shows strong returns from the roof of a building 11–12 ft below the snow surface. Several east–west and south–north crossings of this area showed similar returns. The vertical axis is the depth below the surface (in ft), and the horizontal axis is a linear distance.




- The GPR data revealed cracks, or vertical gaps, in the drifted-in snow along the northern (windward) wall of the crater (Figure 12). This posed a hazard to pedestrian foot traffic; however, we believed the gap was too narrow to threaten vehicle operations, which we communicated to station personnel prior to our departure. Soon after, following safety precautions, such as ropes and harnesses, station personnel used hand tools to probe these gaps, confirming what was observed in the radar data and determining the extent and depth of the vertical gaps (RPSC, pers. comm., 2011). Using heavy equipment to backfill the site as planned closed the cracks to sufficient depth to eliminate their hazard to personnel.

Figure 12. A radar sequence revealing a vertical crack along the northern margin of the blast crater, likely the result of imperfect infilling by blowing snow, predominately from the windward direction. The vertical axis shows the depth below snow grade (ft), and the horizontal axis is a linear distance.

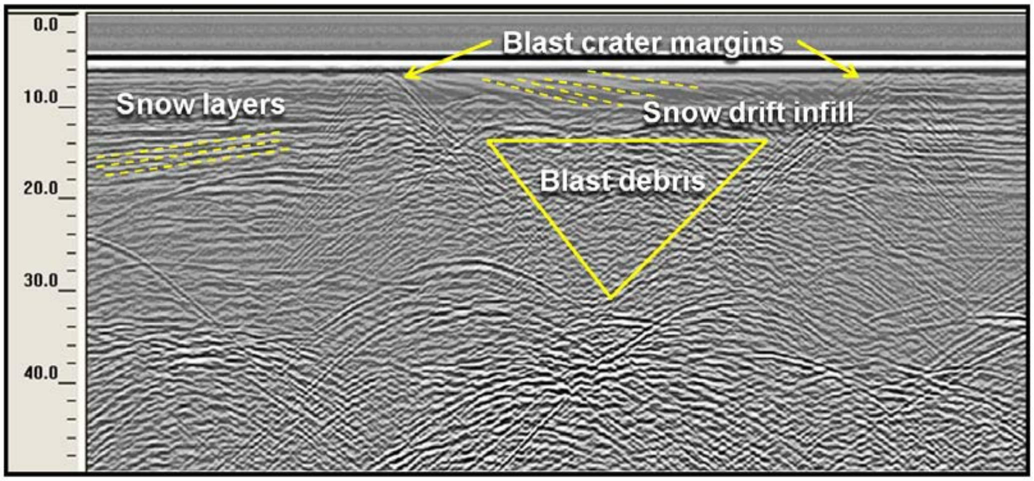



- We clearly identified debris from blasting and the spatial extent of the crater in the GPR profiles (Figure 13). Debris pieces, roughly the size of a football, were apparent throughout the area. Larger debris, perhaps pieces from a roof, etc., may be encountered during backfilling operations.

- The Emergency Generator Vault (Building A20, Figure 2) near the southwestern corner of the survey area did not show any subsurface hazards. This is consistent with the findings during the 2010–2011 survey.

- Building A25 (Supply/Parking and Berthing, Figure 2) appears to be collapsed. Numerous survey lines across this area indicate that the top of the building is now approximately 30 ft below the snow surface.

Figure 13. A radar sequence, modified view from GSSI RADAN v6.6 software, along the eastern boundary, in the north–south direction across buildings A15 and A21. This image shows the interpretation of subsurface features. The vertical axis shows the depth below snow grade, and the horizontal axis is a linear distance.




- It was safe to proceed with planned backfilling operations to harden the Old South Pole site, excluding the areas near buildings A15–A21 and A10 as previously noted. Table 1 provides the coordinates defining these two areas of concern.

Table 1. Coordinates defining areas of concern at Old South Pole test site.

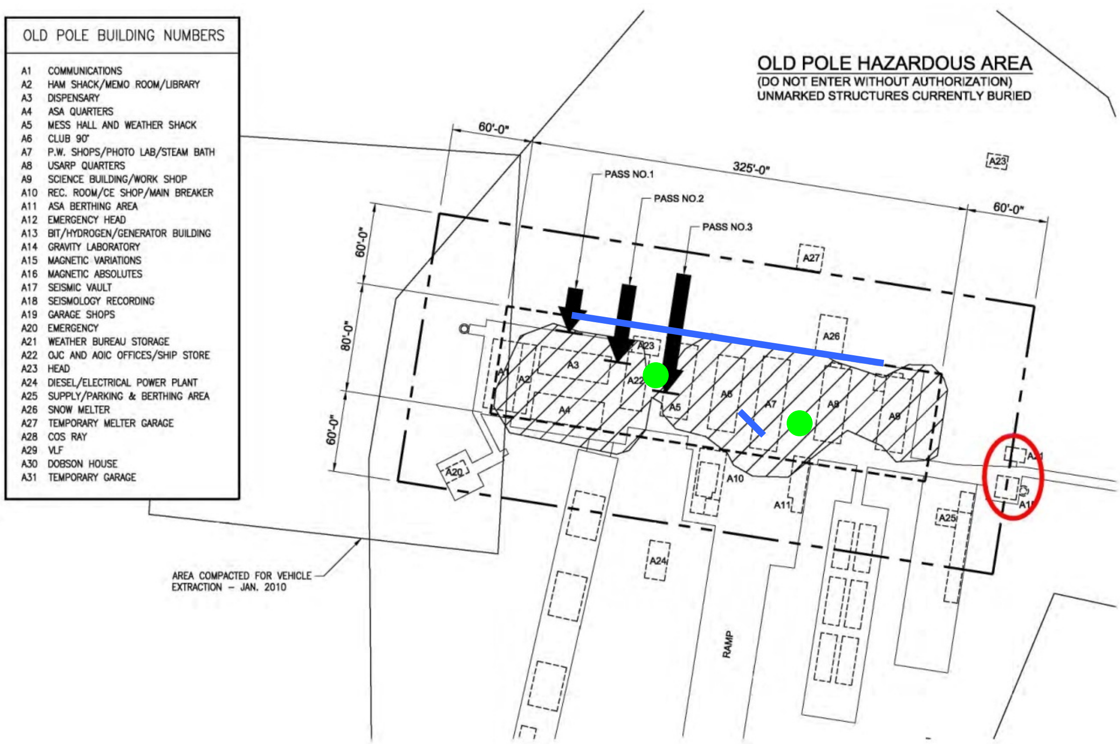
| | | | |
|---|---|---|---|
| A10 area of concern | | | |
| NW | S 89.987509 | NE | S 89.987538 |
| | W 33.026605 | | W 32.873788 |
| | | | |
| SW | S 89.987546 | SE | S 89.987571 |
| | W 33.168313 | | W 33.024401 |
| | | | |
| | | | |
| A15-A21 area of concern | | | |
| NW | S 89.987745 | NE | S 89.987779 |
| | W 30.760089 | | W 30.550436 |
| | | | |
| SW | S 89.987826 | SE | S 89.987866 |
| | W 31.130836 | | W 30.924652 |

## 3.2 Subsurface investigation

### 3.2.1 Located subsurface voids

Along the crater's northern perimeter, the near-surface voids were within approximately 2 ft of the snow surface. Generally, they were small in diameter and bridged by drift snow; and while not considered a hazard to heavy equipment, they presented a greater risk to personnel walking on the snow surface. As anticipated, these shallow voids were primarily located at the interface with the crater wall and drift snow on the windward side (Figure 14). Similar voids were identified downwind.

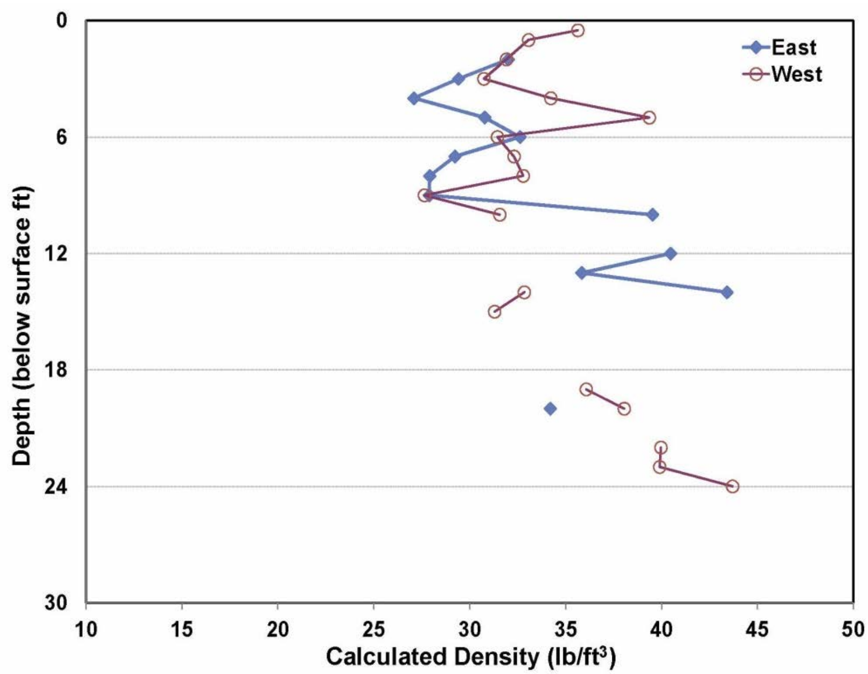
Figure 14. A subsurface investigation within the crater area. *Blue lines* indicate where void locations were found. *Green circles* indicate core locations. The *red circle* indicates the two subsurface buildings identified from the rover GPR survey slated for demolition. (Image by RPSC.)




### 3.2.2 Density profile results

Two cores were collected by RPSC to depths of approximately 25 ft below snow grade to determine the profile of the snow density with depth Figure 15). Within the upper 10 ft from the surface, the density averaged 31.8 lb/ft$^3$. While coring, RPSC visually observed that sections of the core samples varied with some sections containing voids or bits of blast debris. Several samples also contained large snow crystals. On the east side below a depth of 14 ft, core samples could not be obtained as the snow was non-cohesive and exhibited no bonding, attributable to the lack of natural compaction. On the west side at depths below 19 ft, several sections of the core samples had a minimum density of 36.2 $lb/ft^3$. Appendix B provides core density data.

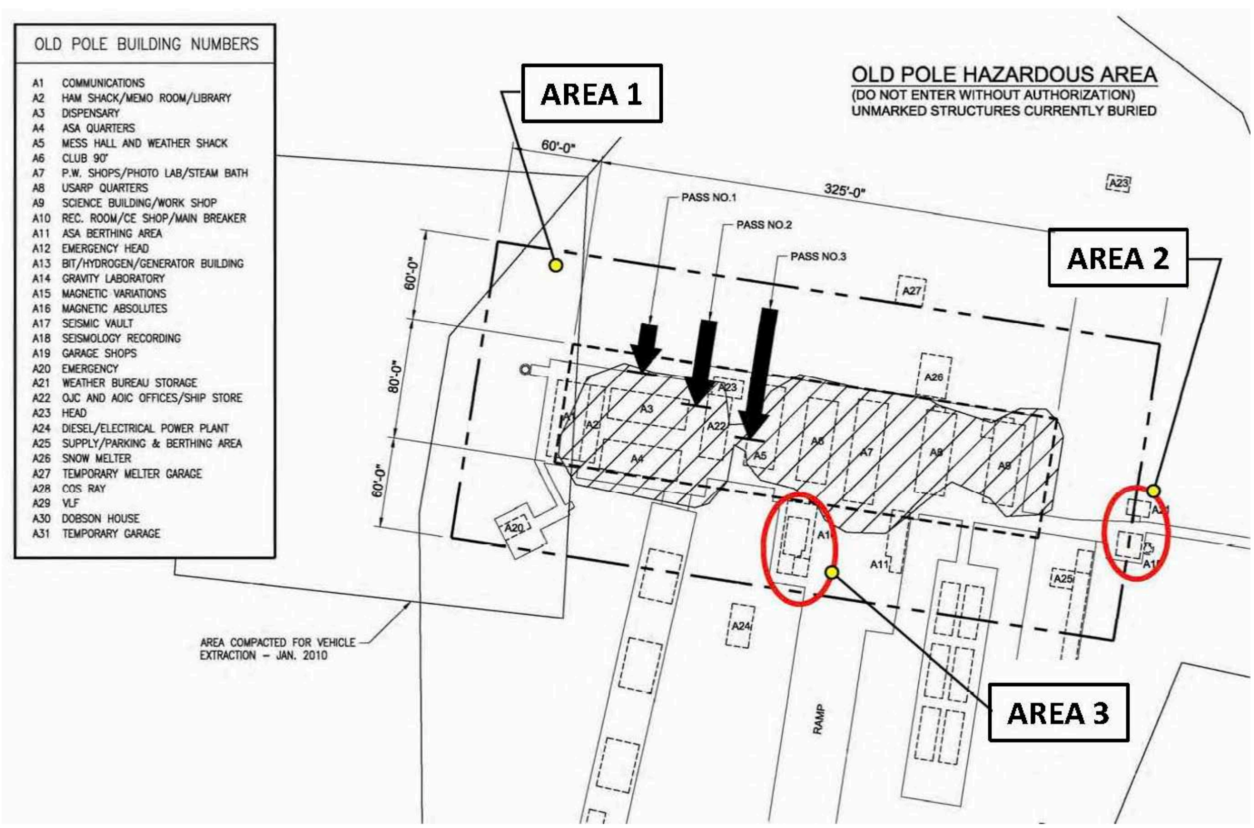
Figure 15. The profile of density with depth calculated from cores collected from within the crater area.



# 4 Remediation Activities

Based on the GPR survey findings, the remediation activities proceeded in three identified areas. As shown in Figure 16, Area 1 consisted of the drifted-in crater. Area 1 was backfilled using heavy equipment. Area 2, located on the eastern perimeter of the test area, consisted of the two Science Buildings (A15 and A21) where GPR reflections indicated intact buildings with rooftop features near the snow surface. The remediation plan called for excavating the snow to expose the buried structures and then backfilling the void with snow into the lowest accessible level of the building. Area 3 was located on the south side of the test area, outside of the crater perimeter, and included the location of Building A10 where strong GPR reflections suggested an intact building 11–13 ft. below the snow surface. Excavation and backfilling, similar to Area 2, was planned.

Figure 16. The three Old South Pole remediation areas identified following the GPR survey. (Image by RPSC.)



## 4.1 Area 1

Backfilling the primary drifted-in crater area was completed in January 2012, in approximately a day, by using two D6 bulldozers (Figure 17). Bulldozers pushed snow in a 3-pass progression (indicated by the arrows in Figure 16), beginning on the northern side of the crater and working around the perimeter. Pass one was a short pass just outside the crater boundary to break through the vertical shear wall created from the blasting. This also broke up any small near-surface voids created from the drift snow, such as the ones identified along the northern boundary of the crater. The second and third passes of the dozers began further away from the center of the crater. Once backfilled, personnel leveled the surface by using a drag. Figure 18 shows Area 1 several days after backfilling was completed. In Figure 18, the flagging on the left side defines the locations of the fuel arches, the area including Building 10, and the Tunnel/Ramp (Figure 16). Concurrent with backfilling Area 1, personnel backfilled the location on the west side of the test area where the D-8 dozer sank into a shallow depression in early 2010.

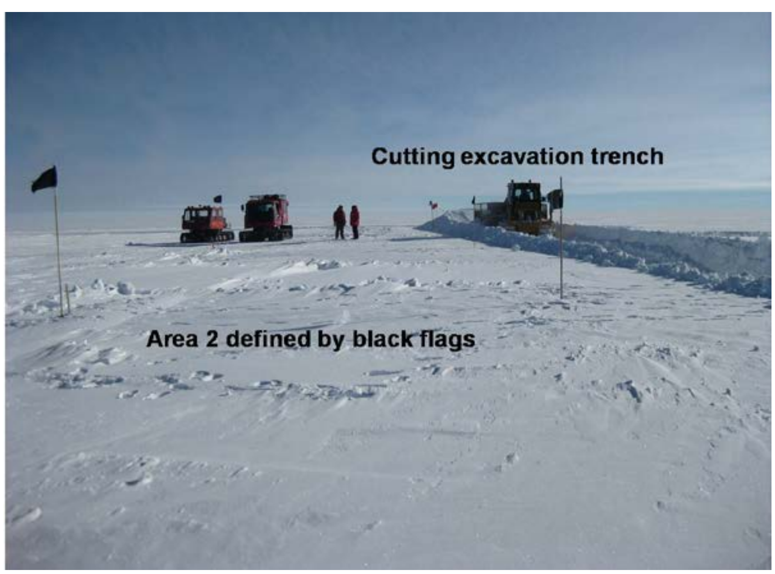
Figure 17. Backfilling Area 1 by pushing snow in a 3-pass progression using bulldozers. The view looks toward the east.

Figure 18. The view looking to the west of the completed Area 1. The flagging on the left side of the photograph identifies the locations of the subsurface fuel arches, the area near Building 10, and the Tunnel/Ramp.


## 4.2 Area 2

On the eastern perimeter in Area 2, the radar reflections indicated near-surface features above the two buried Science Buildings. Due to these unidentified shallow features, excavation proceeded carefully. There was some discrepancy on the location of the buried buildings between the points by the RPSC survey team and the GPS points collected by the rover. To address this, RPSC began the excavation by using a bulldozer to dig a trench, approximately 10 ft deep, perpendicular to the Science Tunnel just to the east of the structures (Figure 19). The trench provided a platform for the excavator, which then carefully uncovered the intact structures.

Figure 19. The north view of the trench excavated in Area 2 adjacent to the buried structures and perpendicular to the buried Science Tunnel.



Excavating below the surface, essentially ground truthing a segment of the GPR data, provided a valuable opportunity. Within 2–3 ft of the surface, we encountered a wooden structure (Figure 20), confirming the interpretation of the radar reflections. As shown in Figure 20, the first feature uncovered was a section of an insulated wall. We believe that the wall section was part of a windscreen positioned on the rooftop of Building A15 facing toward the predominant wind direction.

Figure 20. The excavation of a near-surface structure (Building A15) in Area 2 (17 January 2012).

The excavation continued; and at roughly 20 ft below the snow grade, RPSC uncovered the supporting members of an aluminum-framed square structure, about 20 × 20 ft (Figure 21). We believe, given the depth at which we encountered the main section of this building, that this elevation of the structure served the level between the second and third floors. If so, the floor of the first level might be an additional 16 ft down. The interior of the second floor was mostly filled with snow, suggesting that snow also filled the first level, minimizing the risk of a large void at a depth of 33–41 ft below the snow surface. The excavator was used to remove as much of the exposed ceiling material as possible and to backfill and compact snow into the open cavity to an estimated depth of 30 ft below grade.

On the other side of the Science Tunnel was Building A21, a smaller structure used to store balloon-launch equipment and supplies. Excavation in this vicinity exposed a large mass of ice likely formed from the heat produced by the furnace. The ice mass blocked any deeper excavation. Given the depth of snow cover and the smaller size of the building's footprint, the building was no longer a risk to equipment or to personnel. After examining the condition of Building A21 and the backfilling of Building A15, RPSC backfilled the trench, thus completing the remediation of Area 2.

Figure 21. In Area 2, excavation exposed the supporting members of Building A15, an aluminum-framed square structure. The structural members in the photo are believed to be the ceiling-floor between the second and third floor levels.

## 4.3 Area 3

We defined Area 3, where strong radar reflections were detected, as a 20 × 20 ft area encompassing Building A10 located on the south side of the backfilled crater. Based on an as-built drawing from 1973, next to Building A10 was a structure, believed to be timber-framed, described on maps of the area of Old Pole as a "Builder's Tunnel."

Excavation and backfilling, similar to Area 2, was the planned approach for Area 3. Excavation would expose the buried structure to determine the lowest accessible level of the structure to backfill and compact with snow to significantly reduce the size of the subsurface void and to offer adequate surface stability. The primary contractor cut a trench on the north side of

Area 3 to locate the buried building (Figure 22). This exposed the building's corrugated metal roof (Figure 23) and a nearby chimney.

Figure 22. The trench cut in Area 3 to expose the buried A10 building and to gain access to view the interior.

Figure 23. Corrugated metal roofing material. To the left of the metal roof is the cap on a vent stack for a chimney.

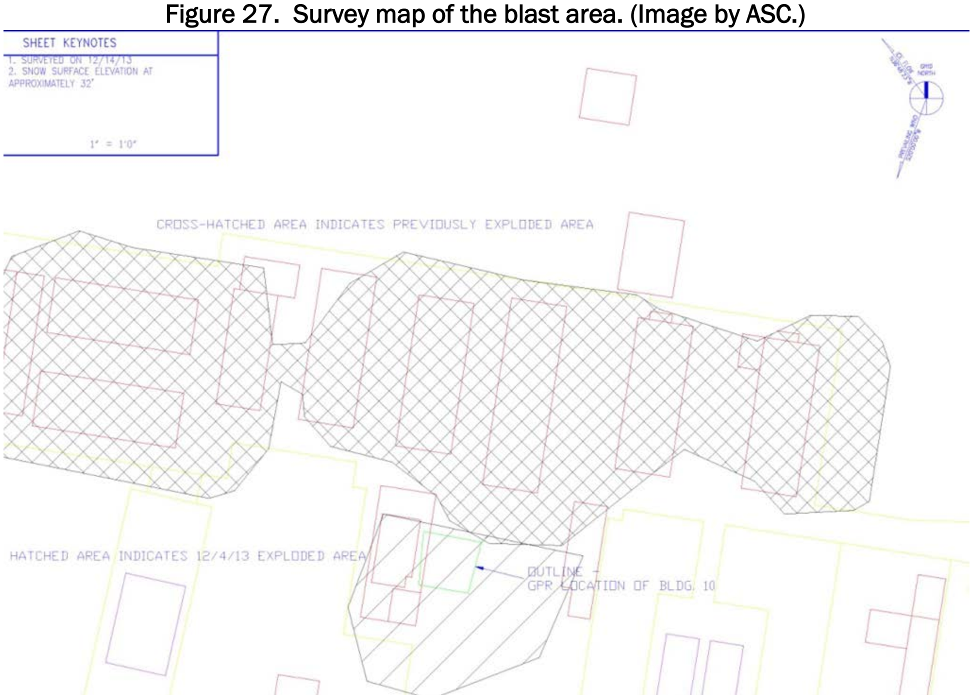
The view inside the metal roof (Figure 24) revealed an intact interior building with a support post between the top of the interior building and the metal roof. Roof joists were visible below the support post, and several electrical conduits ran over the tops of the roof joists. Toward the back of the structure was a bulkhead wall constructed out of framing material. Access into the interior building was not readily visible, preventing us from judging the elevation and span of the interior building and what its function was. Given the complexity of this structure, the primary contractor used blasting to implode the building in December 2013 (Figures 25 and 26). Figure 27 shows the extent of the blasted area. Natural drift snow has now filled the resulting crater.

Figure 24. An interior view of the corrugated metal-roofed building. We believe that the metal roofing covered an interior building. Joists are visible on the bottom of the photo. On the back wall is a bulkhead constructed of lumber. No access to view the dimensions of the interior building was visible.

Figure 25. Explosives placed below the snow surface to implode the buried metal-covered building. (Photo by Antarctic Support Contract [ASC].)

Figure 26. Mounded debris in the blast crater. (Photo by ASC.)

Figure 27. Survey map of the blast area. (Image by ASC.)



# 5 Conclusions

In December 2010, RPSC used explosives to demolish the buried structures forming the principal complex of the original South Pole Station (Old South Pole). These hidden structures, particularly the vertical-access passageways called “top hats,” posed safety risks because the strength of the overlying snow layers was insufficient to support vehicle traffic. Indeed, two unintended vehicle penetrations in early 2010 confirmed this concern. Blasting represented an effective method to implode the below-grade structures to mitigate such risks without affecting ongoing science operations.

Prior to blasting, CRREL engineers used manual methods to perform a GPR study to locate the buried man-made structures, to define their extent, and to determine where to set the charges. The blasting produced a crater approximately 325 ft long and 80 ft wide. Blowing snow during the ensuing winter filled the crater up to the existing grade level.

As GPR is an effective method to identify subsurface features, the purpose of our follow-up GPR survey was to assess the effectiveness of the blasting activities within the crater, to determine if additional subsurface hazards remained within the designated setback area beyond the crater boundary, and to characterize the density conditions with depth within the area of the drifted-in blast crater. In December 2011, we conducted the follow-up GPR survey to assess whether any subsurface hazards remained at the site. In December 2011, we executed the survey using an autonomous polar rover to collect the GPR data and transmitted the radar data, along with GPS track data, to the continental U.S. for expert review and evaluation. The secondary goals of this study evaluated off-site data review and the effectiveness of using an autonomous rover for data collection, new approaches that could be applied elsewhere to support the Antarctic Program. The results from the GPR survey were used to refine the plan to remediate and harden the Old South Pole Station site.

Data collection using the rover was efficient and consistent as Yeti used GPS waypoint navigation to execute closely spaced survey grids over the site on three successive days. Two grids crossed the short axis of the site and one crossed the long axis. Temperatures ranged −22°F to −27°F, and the rover experienced no immobilizations. GPS position accuracy was adequate for these surveys, and Yeti had no obvious resolution issues navigating within a few seconds of 90° south. The radar data were high quality, and transmission rates from the station were sufficiently fast to allow daily off-site review. Daily phone conversations confirmed data quality and improved the off-site reviewer's understanding of survey operations.

Based on these surveys, it appeared that blasting effectively demolished all structures within the crater area, designated as Area 1, and no hazards to vehicle traffic remained within that area. Two additional areas outside the perimeter of the crater posed hazards for equipment and personnel, calling for further attention. Two buildings (A15 and A21) along the eastern perimeter of the site, identified as Area 2, outside of the blast crater, appeared to be intact at depths approximately 10–15 ft below the surface. Strong radar reflections observed in the GPR data near the location of Building A10 suggested an intact building 11–13 ft below the surface. The dimensions of this area were 20 × 20 ft, and it was designated as Area 3. In January 2012, the National Science Foundation approved the remediation plan. Bulldozers backfilled Area 1 in a 3-pass progression, pushing snow followed by leveling and grading. Ground truthing in Areas 2 and 3 used excavation to expose the structures and backfilled them with snow to fill as much of the void as possible. The primary contractor (RPSC) carried out the remediation tasks for Areas 1 and 2 shortly thereafter. Excavation in Area 3 revealed an intact metal-roof structure covering an interior building. To mitigate the subsurface hazards in Area 3, blasting was used during the 2013–2014 austral summer. The resulting crater was allowed to naturally fill with drift snow.

The GPR data revealed a weak interface along the northern (windward) margin of the blast crater between the vertical wall and the drift snow in Area 1. While the interface width was estimated to be too narrow to threaten vehicle operations, this posed a hazard to pedestrian foot traffic. Using hand tools, on-site personnel probed along the interface to determine the depth and extent. Personnel followed safety procedures when conducting the subsurface investigation. As planned, heavy equipment backfilled to close the cracks to sufficient depth to eliminate the hazard to personnel

Consistent with the GPR survey in 2010, the Emergency Generator Vault (Building A20), located in the southwestern corner of the survey area, did not create any subsurface hazards.

Numerous survey transects across the area of Building A25 (Supply/Parking and Berthing) indicated the building was collapsed and that the top of the building was approximately 30 ft below snow grade.

We found both the autonomous rover Yeti and off-site expert data review to be effective for conducting the GPR survey of Old Pole after blasting operations. Simple improvements for future autonomous surveys include the use of a differential GPS base station, minor algorithm changes to improve navigation accuracy, and an overlay of GPS position data directly into GPR data files to improve synchronization. Additionally, the off-site reviewer should be provided with the same Geographic Information System (GIS) used on-site to map rover survey lines.

# 6 Recommendations

Yeti, a rover designed to operate autonomously over polar snowfields, was an effective platform for conducting GPR surveys over a potentially hazardous site. It operated reliably at ambient air temperatures near −22 °F and displayed excellent mobility over the natural, rough snow surface at South Pole. Simple, low-cost improvements to its navigation algorithms and software for survey planning will increase its effectiveness. For specific local sites, such as South Pole and the McMurdo shear zone, adding a differential GPS base station would improve survey accuracy and repeatability. Long-endurance polar rovers, such as the solar-powered, lightweight Cool Robot (Lever et al. 2012), could similarly perform useful GPR surveys over longer distances in Antarctica to help develop safe routes for science and cargo traverses.

Off-site data transfer is a feasible way to access scarce GPR interpretation expertise. Data transfer rates from South Pole are adequate for daily analysis and feedback to field personnel. Besides the radar data, track maps (from autonomous or manual surveys) must also be transferred to allow the off-site analyst to form a clear picture of survey conditions. A key advantage for the present study was that the off-site expert had previous experience with the Old Pole site, having conducted the 2010–2011 GPR survey and assessment. However, access to extensive background information, such as drawings, maps, etc., is essential for anyone off-site to develop a clear understanding of the survey. To aid this, the off-site analyst should possess the same GIS package used on-site to map the surveys.

Good communication tools, timely review of the data, and follow-up discussions via telephone are essential to ensure an effective survey with off-site analysis. About one day's worth of review time is needed for each day of survey data collected.

Additional tasking to continue the remediation and hardening of Old Pole is recommended now that the structures located within and bordering Area 3 have been blasted. We recommend a follow-up GPR survey within the Area 3 crater footprint to assess the effects of the blasting and to characterize the subsurface conditions prior to any additional backfilling. Finally, we recommend a comprehensive survey of the Old Pole area to fully document the site's subsurface conditions after all hardening activities are completed.

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# Appendix A: Summary Table of GPR Files Collected at South Pole

| Radan Filename | Date | File size (MB) | Summary | Yeti Mode |
|---|---|---|---|---|
| _001 | Pre-testing completed without use of Yeti | | | |
| _002 | | | | |
| _003 | | | | |
| _004 | 11/30/2011 | 20.0 | Initial GPR equipment test walk around South Pole Station with GPR equpment towed in sled | N/A |
| _005 | 12/2/2011 | 23.9 | Initial GPR equipment test - walking and towing equipment in sled at Old Pole site | N/A |
| _006 | 12/2/2011 | 26.2 | Initial GPR equipment test - walking and towing equipment in sled at Old Pole site | N/A |
| _007 | 12/4/2011 | 22.7 | Quality Control test with Yeti robot (path repeated the walking survey) | Manual |
| _008 | 12/4/2011 | 7.5 | Survey line on Southewestern corner of flagged area over the Emergency Generator Vault (Bldg A20) | Manual |
| _009 | 12/5/2011 | 34.0 | Manual Survey Western side of flagged survey area. Total of 6 transects Survey transects in North-South/South-North direction | Manual |
| _010 | 12/6/2011 | 33.0 | Survey Western side of flagged survey area. Survey transects in North-South/South-North direction | Auto |
| _011 | 12/6/2011 | 30.4 | Survey Western side of flagged survey area. Survey transects in North-South/South-North direction | Auto |
| _012 | 12/6/2011 | 23.4 | Survey Western side of flagged survey area. Survey transects in North-South/South-North direction | Auto |
| _013 | 12/7/2011 | 29.4 | Survey Eastern side of flagged survey area. Survey transects in North-South/South-North direction | Auto |
| _014 | 12/7/2011 | 26.4 | Survey Eastern side of flagged survey area. Survey transects in North-South/South-North direction | Auto |
| _015 | 12/7/2011 | 21.6 | Survey Eastern side of flagged survey area. Survey transects in North-South/South-North direction | Auto |
| _016 | 12/8/2011 | 30.0 | Survey West-East/East-West direction of flagged area Survey transects in North-South/South-North direction | Auto |
| _017 | 12/8/2011 | 29.3 | Survey West-East/East-West direction of flagged area Survey transects in North-South/South-North direction | Auto |
| _018 | 12/8/2011 | 38.3 | Survey West-East/East-West direction of flagged area Survey transects in North-South/South-North direction | Auto |
| _019 | 12/9/2011 | 42.6 | Re-survey of point of interest 1 (18A)[1] | |
| _020 | 12/9/2011 | 39.9 | Re-survey of point of interest 1 (18B)** | |
| _021 | 12/9/2011 | 31.6 | Re-survey of point of interest 1 (18C)** | |

Note:

[1] File uploaded to AMRDEC. Survey location determined incorrect due to GPR and GPS time shift.

** File was not transferred to AMRDEC. Survey location incorrect due to GPR and GPS time shift.

# Appendix B: Snow Density Measurements

Table B1. Snow density measurements for east location. (Table provided by RPSC.)

**Snow Density for East Cylindrical Samples**

| Date | Core Sample Location | Time | Sample ID | Diameter D (cm) | Height h (cm) | Weight M (grams) | Density p (g/cm$^3$) | Notes |
|---|---|---|---|---|---|---|---|---|
| 19-Dec-11 | E1 | 1400 | East Hole; From Top of Sample: 1' | | | | | top of sample crumbled; no hardpack |
| 19-Dec-11 | E2 | 1400 | East Hole; From Top of Sample: 2' | 9.5 | 5.5 | 200 | 0.51 | |
| 19-Dec-11 | E3 | 1400 | East Hole; From Top of Sample: 3' | 9.8 | 4.5 | 160 | 0.47 | |
| 19-Dec-11 | E4 | 1400 | East Hole; From Top of Sample: 4' | 10 | 4.4 | 150 | 0.43 | very light and large sugary crystals |
| 19-Dec-11 | E5 | 1400 | East Hole; From Top of Sample: 5' | 8.8 | 8 | 240 | 0.49 | misshapen -- diameter 98mm/78mm took avg |
| 19-Dec-11 | E6 | 1410 | East Hole; From Top of Sample: 6' | 9.2 | 5.9 | 205 | 0.52 | sides pitted; there were some voids in this core (level 6'-10') |
| 19-Dec-11 | E7 | 1410 | East Hole; From Top of Sample: 7' | 9.4 | 10 | 325 | 0.47 | nice core |
| 19-Dec-11 | E8 | 1410 | East Hole; From Top of Sample: 8' | 9.5 | 16.4 | 520 | 0.45 | |
| 19-Dec-11 | E9 | 1410 | East Hole; From Top of Sample: 9' | 9.5 | 10.1 | 320 | 0.45 | |
| 19-Dec-11 | E10 | 1410 | East Hole; From Top of Sample: 10' | 9.2 | 5.7 | 240 | 0.63 | slightly pitted sample |
| 19-Dec-11 | E11 | 1420 | East Hole; From Top of Sample: 11' | | | | | 1' voids in coring -- drill would drop at levels 11-15' |
| 19-Dec-11 | E12 | 1400 | East Hole; From Top of Sample: 12' | 9.4 | 5.4 | 243 | 0.65 | |
| 19-Dec-11 | E13 | 1420 | East Hole; From Top of Sample: 13' | 9.4 | 14 | 558 | 0.57 | |
| 19-Dec-11 | E14 | 1420 | East Hole; From Top of Sample: 14' | 8.2 | 4.9 | 180 | 0.70 | Sugary; big crystals, not perfectly round |
| 19-Dec-11 | E15 | 1420 | East Hole; From Top of Sample: 15' | | | | | samples crumbled |
| 19-Dec-11 | E16 | 1430 | East Hole; From Top of Sample: 16' | | | | | samples crumbled -- most of core was sugar |
| 19-Dec-11 | E17 | 1430 | East Hole; From Top of Sample: 17' | | | | | samples crumbled |
| 19-Dec-11 | E18 | 1430 | East Hole; From Top of Sample: 18' | | | | | samples crumbled |
| 19-Dec-11 | E19 | 1430 | East Hole; From Top of Sample: 19' | | | | | samples crumbled |
| 19-Dec-11 | E20 | 1430 | East Hole; From Top of Sample: 20' | 8.8 | 8.4 | 280 | 0.55 | Sugary |
| 19-Dec-11 | E21 | 1440 | East Hole; From Top of Sample: 21' | | | | | Samples all crumbled; entire core was sugary |
| 19-Dec-11 | E22 | 1440 | East Hole; From Top of Sample: 22' | | | | | no samples possible |
| 19-Dec-11 | E23 | 1440 | East Hole; From Top of Sample: 23' | | | | | no samples possible |
| 19-Dec-11 | E24 | 1440 | East Hole; From Top of Sample: 24' | | | | | no samples possible |
| 19-Dec-11 | E25 | 1440 | East Hole; From Top of Sample: 25' | | | | | no samples possible |

Table B2. Snow density measurements for west location. (Table provided by RPSC.)

**Snow Density for West Cylindrical Samples**

| Date | Core Sample Location | Time | Sample ID | Diameter D (cm) | Height h (cm) | Weight M (grams) | Density p (g/cm$^3$) | Notes |
|---|---|---|---|---|---|---|---|---|
| 19-Dec-11 | W.5 | 1510 | West Hole; From Top of Sample: .5' | 9 | 4.9 | 178 | 0.57 | |
| 19-Dec-11 | W1 | 1510 | West Hole; From Top of Sample: 1' | 9.4 | 6.5 | 239 | 0.53 | |
| 19-Dec-11 | W2 | 1510 | West Hole; From Top of Sample: 2' | 9.5 | 6.4 | 232 | 0.51 | |
| 19-Dec-11 | W3 | 1510 | West Hole; From Top of Sample: 3' | 9.7 | 5 | 182 | 0.49 | |
| 19-Dec-11 | W4 | 1510 | West Hole; From Top of Sample: 4' | 9.3 | 5.1 | 190 | 0.55 | |
| 19-Dec-11 | W5 | 1510 | West Hole; From Top of Sample: 5' | 9.1 | 3.9 | 160 | 0.63 | |
| 19-Dec-11 | W6 | 1520 | West Hole; From Top of Sample: 6' | 9.5 | 4.9 | 175 | 0.50 | |
| 19-Dec-11 | W7 | 1520 | West Hole; From Top of Sample: 7' | 9.3 | 8.9 | 313 | 0.52 | |
| 19-Dec-11 | W8 | 1520 | West Hole; From Top of Sample: 8' | 9.2 | 7.1 | 248 | 0.53 | |
| 19-Dec-11 | W9 | 1520 | West Hole; From Top of Sample: 9' | 9.1 | 12.5 | 360 | 0.44 | |
| 19-Dec-11 | W10 | 1520 | West Hole; From Top of Sample: 10' | 9.5 | 5.3 | 190 | 0.51 | |
| 19-Dec-11 | W11 | 1530 | West Hole; From Top of Sample: 11' | | | | | crumbs |
| 19-Dec-11 | W12 | 1530 | West Hole; From Top of Sample: 12' | | | | | crumbs |
| 19-Dec-11 | W13 | 1530 | West Hole; From Top of Sample: 13' | | | | | crumbs |
| 19-Dec-11 | W14 | 1530 | West Hole; From Top of Sample: 14' | 9.6 | 4.2 | 160 | 0.53 | good sample |
| 19-Dec-11 | W15 | 1530 | West Hole; From Top of Sample: 15' | 9.4 | 10.2 | 355 | 0.50 | good sample |
| 19-Dec-11 | W16 | 1540 | West Hole; From Top of Sample: 16' | | | | | blast debris; crumbly |
| 19-Dec-11 | W17 | 1540 | West Hole; From Top of Sample: 17' | | | | | crumbs |
| 19-Dec-11 | W18 | 1540 | West Hole; From Top of Sample: 18' | | | | | crumbs |
| 19-Dec-11 | W19 | 1540 | West Hole; From Top of Sample: 19' | 7.9 | 2.4 | 68 | 0.58 | crumbs, not quite cylindrical |
| 19-Dec-11 | W20 | 1540 | West Hole; From Top of Sample: 20' | 8.2 | 5.9 | 190 | 0.61 | misshapen; contained blast debris and pits |
| 19-Dec-11 | W21 | 1550 | West Hole; From Top of Sample: 21' | | | | | crumbs and sugar |
| 19-Dec-11 | W22 | 1550 | West Hole; From Top of Sample: 22' | 9.4 | 7.2 | 320 | 0.64 | good sample |
| 19-Dec-11 | W23 | 1550 | West Hole; From Top of Sample: 23' | 9.2 | 8 | 340 | 0.64 | good sample |
| 19-Dec-11 | W24 | 1550 | West Hole; From Top of Sample: 24' | 9.2 | 2.9 | 135 | 0.70 | dirty sample, but very hard |
| 19-Dec-11 | W25 | 1550 | West Hole; From Top of Sample: 25' | | | | | hit something, so didn't drill further |

# REPORT DOCUMENTATION PAGE

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Remediation of Old South Pole Station Using Autonomous Data Collection and Remote Assessment of Ground-Penetrating Radar

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**14. ABSTRACT**
This report describes a ground-penetrating-radar (GPR) survey assessing the effectiveness of blasting subsurface hazards at the original South Pole Station. Hidden under layers of accumulated snow, false attic structures ("top hats") were built on top of the original buildings to displace the increasing snow depth. By causing an alteration in the snow structure through enhanced metamorphism, the presence of these structures and heat from the buildings reduced the bearing capacity of the overlying snow to support surface-based heavy vehicle.

Blasting was an effective method to mitigate the subsurface safety risks posed to personnel and equipment operating in the area. The resulting blast crater naturally filled with drift snow. An autonomous polar rover was deployed and successfully conducted a post-blast GPR survey operating at ambient temperatures of −22°F or lower. Expert review of the GPR data confirmed that the targeted structures within the crater were effectively demolished. Data collected by the rover revealed two sites beyond the crater perimeter, yet within the survey area, that posed a risk to heavy vehicles. A mitigation effort included these two areas. Data collection with an autonomous rover and off-site expert data review proved to be effective tools for use at South Pole.

**15. SUBJECT TERMS**

| | | |
|---|---|---|
| | Blasting | Ground-penetrating radar |
| Antarctica | Buried man-made structures | NSF |
| Autonomous polar rover | EPOLAR | South Pole |

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