AUTONOMOUS SURVEYING OF SEA-ICE THICKNESS

Main Category:	Surveying
Sub Category:	-
Course #:	SUR-119
Course Content:	24 pgs
PDH/CE Hours:	1

OFFICIAL COURSE/EXAM
(SEE INSTRUCTIONS ON NEXT PAGE)

SUR-119 EXAM PREVIEW

Instructions:

- At your convenience and own pace, review the course material below. When ready, click "Take Exam!" above to complete the live graded exam. (Note it may take a few seconds for the link to pull up the exam.) You will be able to re-take the exam as many times as needed to pass.
- Upon a satisfactory completion of the course exam, which is a score of 70% or better, you will be provided with your course completion certificate. Be sure to download and print your certificates to keep for your records.

Exam Preview:

1. According to the reference material, the bearing capacity of sea ice depends on the thickness, structure, and temperature of the ice.
   a. True
   b. False
2. Sea ice grows on McMurdo Sound through the winter and reaches thicknesses in excess of _ m by station opening in early October.
   a. 1
   b. 2
   c. 3
   d. 4
3. The guidance notes that ice thickness is the most critical parameter, and it requires a minimum of __ borehole ice-thickness measurements distributed along the runway with repeat measurements at time intervals ranging from weekly to daily during flight periods.
   a. 8
   b. 12
   c. 16
   d. 24
4. According to the reference material, because the conductivity of seawater is much lower than that of air, snow, or sea-ice, apparent conductivity largely depends on the distance between the instrument and the seawater.
   a. True
   b. False

5. Using Table 2. Borehole measurements of show depth and ice thickness and corresponding EM31 ice-thickness measurements, what was the largest reported error (%)?
    a. -2.1 %
    b. 2.6 %
    c. 11.1 %
    d. 15.6 %

6. According to the reference material, if conducted without stops, the autonomous survey would have taken only 16 min, or about the same time as one borehole measurement.
    a. True
    b. False

7. Yeti is a 4-wheel-drive, battery-powered rover co-developed by Dartmouth College and CRREL According to the reference material, what was the average survey speed of the Yeti?
    a. 0.8 m/s
    b. 1.0 m/s
    c. 1.2 m/s
    d. 1.5 m/s

8. Using Table 1. Parameter values for Equation (1) from available sources, what was the value of C (mS/m) for Landfast sea ice near Barrow, AK as determined by Dilliplaine et al. (2013)?
    a. 22
    b. 45
    c. 57
    d. 170

9. Based on the Shear Zone surveys, average rover power consumption was 340 W, which allowed the rover's 1200 Wh battery pack to provide 3.5 h of operation or __ km of survey length between battery changes.
    a. 15
    b. 18
    c. 20
    d. 22

10. According to the reference material, the EM31 measures apparent conductivity (mS/m) of the terrain beneath the instrument. The transmitter operates at 6.8 kHz, and the transmitter and receiver coils are separated by 3.66 m.
    a. True
    b. False

Cold Regions Research and Engineering Laboratory

US Army Corps of Engineers®
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Engineering for Polar Operations, Logistics, and Research (EPOLAR)

Autonomous Sea-Ice Thickness Survey

James H. Lever   June 2016

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Autonomous Sea-Ice Thickness Survey

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Final Report

Abstract

We conducted an autonomous survey of sea-ice thickness using the Polar rover *Yeti* to tow an electromagnetic induction meter over sea ice in McMurdo Sound, Antarctica. This proof-of-concept survey aimed to demonstrate improved efficiency relative to manual surveys routinely conducted to assess the safety of roads and runways constructed on the sea ice. *Yeti* executed the autonomous survey on 11 November 2014. This report describes the methods used, compares the measured ice-thickness profiles with manual borehole measurements, assesses the merits of autonomous surveys relative to manual ones, and describes potential future applications.

Contents

Figures and Tables

Figures

Tables

Preface

Acronyms and Abbreviations

AFCESA   Air Force Civil Engineer Support Agency

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

NSF   National Science Foundation

PLR   Division of Polar Programs

USAP   U.S. Antarctic Program

1   Introduction

1.1   Background

McMurdo Station is the largest facility operated under the U.S. Antarctic Program (USAP) and is the logistics and transportation hub for USAP's South Pole Station and deep-field science camps. The station itself is located on the southern tip of Ross Island, bordered by the McMurdo Sound to the west and the Ross Sea to the east (Figure 1). Sea ice grows on McMurdo Sound through the winter and reaches thicknesses in excess of 2 m by station opening in early October. This sea ice typically can support heavy vehicles and cargo aircraft through late November or early December. Easy access and proximity to the station has made the sea ice attractive as a location for an aircraft runway, runway access roads, and roads to research and logistics sites around McMurdo Sound.

Figure 1. The runway and roads on McMurdo Sound sea ice in November 2009. (Map data: Google, DigitalGlobe.)

The bearing capacity of sea ice depends on the thickness, structure, and temperature of the ice. The U.S. Air Force operates the cargo aircraft re-supplying McMurdo Station, and its Air Force Civil Engineer Support Agency (AFCESA) has established methods to determine safe landing and parking loads for the sea-ice runway (AFCESA 2007). The guidance notes that ice thickness is the most critical parameter, and it requires a minimum of 16 borehole ice-thickness measurements distributed along the runway with repeat measurements at time intervals ranging from weekly to daily during flight periods. For known ice thickness, the guidance provides allowable aircraft loads and parking times, binned according to measured surface-ice temperatures.

Using similar ice-temperature bins, Weale and Sodhi (2015) calculated the required ice thickness to support heavy tracked vehicles traversing McMurdo Sound to resupply a fuel cache and camp at Marble Point. They did not specify the spatial or temporal distributions of ice-thickness measurements, but the route is about 80 km long. Conducting manual borehole measurements with separation distances even as long as one kilometer would be a substantial undertaking for each resupply traverse.

USAP personnel currently measure ice thickness manually. Each measurement requires clearing the surface snow, drilling a borehole by using a powered ice auger, measuring ice thickness with a toggled line, and recording the result in a logbook. The location of the borehole is also recorded using a handheld global positioning system (GPS) receiver. The thickness measurements must then be analyzed and combined with the GPS data to determine the thickness distribution and the locations of any areas of concern. Each thickness measurement takes about 15 min to execute in addition to post-processing time and travel time between locations.

1.2 Objectives

Researchers at U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) and Dartmouth College have collaborated to develop the Polar rover *Yeti* to conduct autonomous ground-penetrating radar surveys to detect and map subsurface crevasses and other safety hazards. We sought to use the rover to conduct proof-of-concept autonomous surveys of sea-ice thickness in McMurdo Sound to demonstrate improved efficiency relative to manual surveys.

1.3   Approach

We conducted an autonomous survey of sea-ice thickness using *Yeti* to tow an electromagnetic induction meter over sea ice in McMurdo Sound, Antarctica. This proof-of-concept survey aimed to demonstrate improved efficiency relative to manual surveys routinely conducted to assess the safety of roads and runways constructed on the sea ice. *Yeti* executed the autonomous survey on 11 November 2014 (Figure 2). This report describes the methods used, compares the measured ice-thickness profiles with manual borehole measurements, assesses the merits of autonomous surveys relative to manual ones, and describes potential future applications.

Figure 2. *Yeti* towing an EM31 electromagnetic ice-thickness meter along the Pegasus Cut-Off Road near McMurdo Station, Antarctic, on 11 November 2014.

2 Equipment and Methods

Yeti is a 4-wheel-drive, battery-powered rover co-developed by Dartmouth College and CRREL. *Yeti* has successfully conducted over-snow, ground-penetrating-radar (GPR) surveys in Greenland and Antarctica to detect and map buried hazards (Lever et al. 2013; Lever et al. 2016).

We shipped *Yeti* to Antarctica in 2014 under National Science Foundation, Division of Polar Programs (NSF-PLR), science grants 1246400 and 1245915 to conduct systematic GPR surveys across a crevasse-ridden section of the shear zone between the Ross and McMurdo Ice Shelves and thereby gain insight into its state of fracture and long-term stability. In November 2014, *Yeti* conducted over 600 km of autonomous GPR surveys across this 5.7 km wide shear zone, operating continuously for seven days with stops only to change batteries and to store data (Figure 3). It experienced no immobilizations, and other than two operator-induced errors, it completed each over-and-back survey run on schedule. The autonomous sea-ice survey leveraged this field deployment.

Figure 3. *Yeti* with a GPR sled in the McMurdo Shear Zone. The black case housed the radar controller, batteries, and GPS receiver and supported the GPS antenna (*white disk*). The orange 200 MHz antenna and smaller 400 MHz antenna (not visible) mounted in front of the black case. The black polyethylene sled included two steel rudders to reduce yaw motions. The sled and GPR equipment weighed 74 kg. *Yeti's* radio antenna carried a red flag; its GPS antenna mounted on the opposite side in front of the battery box.

We conducted the sea-ice thickness survey after *Yeti's* deployment in the Shear Zone. We swapped the GPR equipment for a Geonics EM31 electromagnetic induction meter to measure ice-thickness and towed it in the

same sled (Figure 4). The rover weighed 77 kg, and the sled with the EM31 weighed 13 kg. The average survey speed was 5.3 km/h (1.5 m/s). Based on the Shear Zone surveys, average rover power consumption was 340 W, which allowed the rover's 1200 Wh battery pack to provide 3.5 h of operation or 18 km of survey length between battery changes. The GPS receiver on *Yeti* typically saw 18–22 satellites, with position accuracy (horizontal dilution of precision) of 0.6–0.7 m. The resulting survey lines normally deviated only 1–2 m from a straight line between the two end waypoints.

Figure 4. The EM31 in the sled towed by *Yeti* along Pegasus Cut-Off Road on McMurdo Sound sea ice. The blue box housed the battery-powered EM31 electronics. The instrument's horizontal, white-plastic poles separated the transmitter and receiver coils by 3.66 m. The sled also carried a small datalogger and a GPS receiver (not visible). The survey crew conducted three manual borehole ice-thickness measurements to compare with data from the EM31.
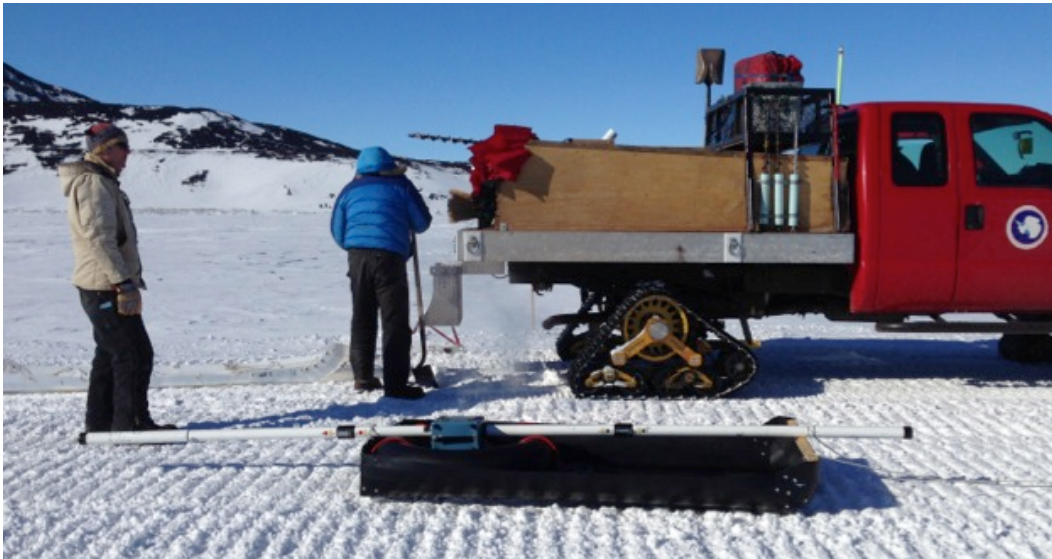
The EM31 measures apparent conductivity (mS/m) of the terrain beneath the instrument (Geonics 2010). A transmitter coil at one end of the instrument induces circular eddy current loops in the terrain, and the receiver coil at the other end senses the resulting magnetic fields. The transmitter operates at 9.8 kHz, and the transmitter and receiver coils are separated by 3.66 m. The instrument does not require electrical contact with the terrain, and it is calibrated to read the correct conductivity when the terrain is uniform.

For layered terrain, the apparent conductivity is a distance-weighted average over the several-meter footprint of the instrument. The problem simplifies for the horizontally layered air-snow-ice-seawater terrain of interest

here. Because the conductivity of seawater (2400–2500 mS/m) is much higher than that of air, snow, or sea-ice (0–80 mS/m), apparent conductivity largely depends on the distance between the instrument and the seawater. Secondary effects include the extent of brine inclusion in the sea ice and the presence of under-ice, low-salinity meltwater.

Numerous studies have used the EM31 for sea-ice thickness surveys (e.g., Kovaks and Morey 1991; Haas et al. 1997, 2011; Eicken et al. 2001; Haas and Eicken 2001; Mahoney et al. 2007). Because apparent conductivity falls off exponentially with distance to the seawater, most studies have used a logarithmic relationship to convert instrument readings of apparent conductivity, σ_a, into distance to the seawater, D_{sw}:

$$D_{sw} = A - B\ln(\sigma_a - C) \tag{1}$$

where the coefficients A, B, and C are determine by best-fitting EM31 readings with measured ice thickness for the conditions of interest. The asymptote $\sigma_a = C$ is interpreted as the conductivity of an infinitely thick slab of sea ice. Ice thickness, H_{ice}, is then obtained by subtracting the height of the instrument above the ice (air plus snow heights) from D_{sw}. Table 1 provides for Equation (1) a list of parameters from several sources.

Table 1. Parameter values for Equation (1) from available sources.

Source	Ice Conditions	A (m)	B (m)	C (mS/m)
Haas et al. (1997)	Central Arctic Ocean	7.0–7.9	1.0–1.1	57–96
Eicken et al. (2001)	Northern Chukchi Sea	8.2	1.2	57
Haas and Eicken, (2001)	Central Arctic Ocean	7.9–8.4	1.1–1.2	57–80
Haas et al. (2011)	Central Arctic Ocean	8.2	1.2	45
Mahoney et al. (2007)	Landfast sea ice near Barrow, AK	4.4–9.0	0.6–1.4	67–170
Dilliplaine et al. (2013)	Landfast sea ice near Barrow, AK	8.6	1.3	22

Eicken et al. (2001) summarized sources of uncertainty in EM31-based ice-thickness measurements and estimated that, compared with borehole measurements, their errors averaged 0.05 m for 2 m of level sea ice. They attributed most of the uncertainty to differences in the sampled footprints, namely less than 0.2 m for boreholes versus more than 2 m for the EM31. Haas and Eicken (2001) found average errors of 6% or 0.12 m for 2 m of ice, although their measurements included deformed and ridged ice that probably increased average errors.

For our study, the EM31 was equipped with an Archer handheld computer for system setup and data logging. We set it to sample at 5 Hz and synchronized its clock (within 1 s) with a Garmin 60CSx GPS receiver to geo-reference the survey. That GPS unit saw 10–12 satellites, resulting in horizontal position accuracy of 2–3 m.

3   Results

On 11 November 2014, we conducted the autonomous ice-thickness survey adjacent to the Pegasus Short-Cut Road near the transition from McMurdo Station (Figure 5). The survey course consisted of a 0.82 km outbound (southward) leg and a 0.56 km inbound (northward) leg on either side of the road for a total course length of 1.4 km. The run itself included three stops for manual borehole measurements of snow depth and ice thickness.

Figure 5. The *Yeti*-EM31 survey track plot. GPS track points (*circles*) were logged at 10 s intervals. The course was north–south along the Pegasus Cut-Off Road near the sea-ice transition at McMurdo Station. The background image was acquired 29 October 2014. (Map data: Google, DigitalGlobe.)
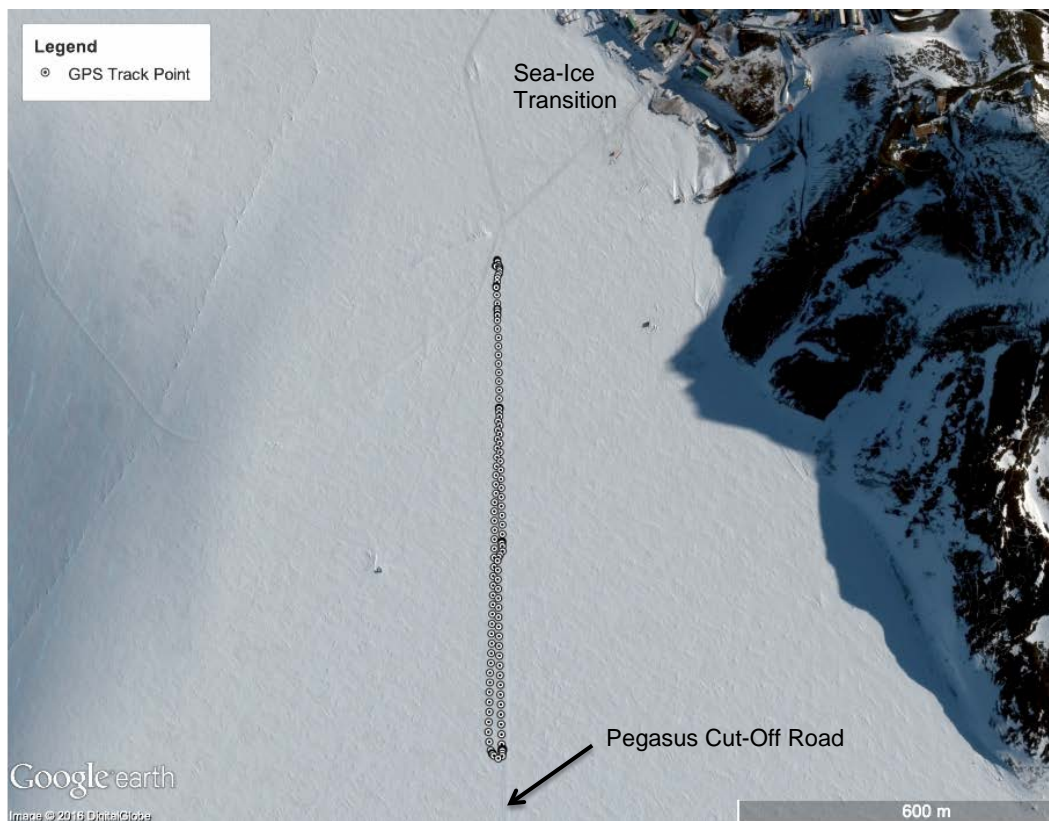

Table 2 summarizes the manual borehole measurements. Time constraints of the survey crew limited the number of boreholes, but the measurements showed relatively uniform snow depth and ice thickness.

Table 2. Borehole measurements of show depth and ice thickness and corresponding EM31 ice-thickness measurements.

Time	Ice Thickness (m)	Snow Depth (m)	EM31 Ice Thickness (m)	Error (m)	Error (%)
15:09:00	2.01	0.56	2.06	−0.05	2.6
15:20:00	2.08	0.46	2.04	0.04	−2.1
15:40:00	2.13	0.56	2.37	−0.24	11.1

Table 2 also compares the borehole-measured ice thicknesses with the corresponding values calculated from *Yeti's* EM31 readings nearby. We tried several published conversion equations and found reasonable agreement with the borehole measurements by using the following equation to convert the apparent conductivity to the depth to the saltwater interface:

$$D_{sw} = 8.64 - 1.26 ln(\sigma_a - 21.9) \tag{2}$$

This specific conversion was based on an unpublished report archived at the University of Alaska (Dilliplaine et al. 2013). That report described a systematic method to calibrate the EM31 by placing it over level, land-fast sea ice and raising the instrument in increments to increase D_{sw}. This approach avoids the need to find level ice of different thicknesses to conduct a calibration. It also avoids mixing non-uniform ice conditions into the calibration, a concern expressed by several of the published sources listed in Table 1.

To obtain ice thickness, we subtracted the average height of the EM31 coils (0.30 m) and the average snow depth (0.52 m) from the calculated D_{sw} values. The resulting errors averaged 3.9% of the readings (Table 2), a reasonably low value.

Figure 6 shows the continuous record of ice thickness obtained from the survey compared with the borehole measurements. For convenience, we converted GPS-based geographic coordinates to distance from the survey origin.

Figure 6. A continuous record of measured ice thickness from the EM31 compared with borehole measurements. The distance from the origin is based on GPS coordinates.
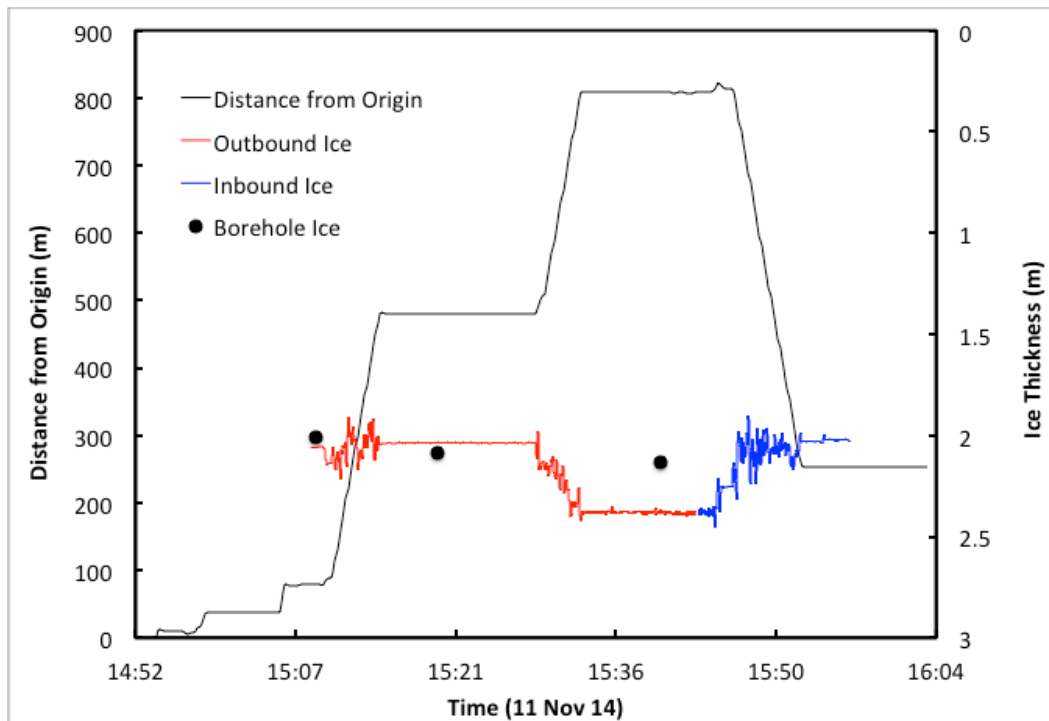
As seen in Figure 6, variations in the EM31-based thickness measurements were small during stationary periods of the borehole measurements and increased during the autonomous survey sections. The lower-frequency variation probably reflects real variations in ice thickness of about ±0.1 m while the higher-frequency variations probably resulted from movement of the arms of the instrument over rough snow.

As measured by the EM31, ice thickness varied 2.0–2.4 m with a clear trend of increasing thickness towards the south (outbound) end of the course. Note that the third borehole measurement captured only 0.1 m of the 0.3 m increase in ice thickness seen in the EM31 readings. The general agreement in shape of the outbound and inbound EM31 profiles provides some confidence that the measured increase in ice thickness over the 500–800 m section of the route was a real effect. As noted, the EM31 samples a larger footprint of ice compared with borehole measurements. It is likely that the third borehole sampled a locally thin area of ice, suggesting that the underside of the ice cover was rougher than the relatively smooth top surface. In general, widely spaced borehole measurements can insufficiently sample areas of varying ice thickness, which could be important for assessing sea-ice safety for aircraft and vehicles.

4   Discussion and Recommendations

We met our objective to demonstrate that autonomous sea-ice thickness surveys offer improved efficiency relative to manual surveys. The rover *Yeti* was able to conduct 1.4 km of measurements at 5 Hz, or one measurement every 0.3 m, with average error under 4% based on limited borehole measurements. If conducted without stops, the autonomous survey would have taken only 16 min, or about the same time as one borehole measurement. Scaled up, four survey lines along a 3000 m sea-ice runway at 20 m line spacing (12 km total survey length) would take 2.3 h, or about the same time as nine borehole measurements. Autonomous surveys thus offer the potential for significantly higher spatial resolution and coverage than is practical for manual surveys.

Reliable equipment now exists to conduct routine autonomous ice-thickness surveys to support Antarctic operations. The EM31 is a commercial product with a long record of deployments to measure sea-ice thickness. It is reliable and easy to use by technical personnel (e.g., surveyor or science technician). *Yeti*, although custom-made, has displayed excellent reliability and mobility over polar snowfields. It is also easy for technical personnel to operate and maintain. With two sets of batteries, *Yeti* could conduct 38 km of autonomous surveys on sea ice in 7 h. All of the data are geo-referenced, so areas of concern (i.e., locally thin ice) can be relocated and assessed in greater detail if needed. The data can readily be mapped using a standard geographic information system (GIS), such as ArcMap or Google Earth, which can then display the data relative to geographic and man-made features of interest.

Initially, mobilization, demobilization, and data-processing times would likely be longer for autonomous surveys than for manual ones until USAP personnel become more experienced with autonomous surveys. In the present case, the author operated *Yeti* and the EM31. We parked *Yeti* overnight at the McMurdo sea-ice transition after our shear-zone field-work. It took less than an hour to install batteries, attach the sled, mount and initialize the EM31, send the survey coordinates, and begin the survey. Post-processing of the data to create ice-thickness profiles took about 4 h but would be faster with frequent, routine surveys. Manual borehole measurements would still be needed periodically to check the calibration of the EM31, but personnel deploying the rover could make these measurements while the rover executes the survey. The calibration process

could subsequently be streamlined if the results produce similar calibration curves each year.

For routine surveys, data processing can be semi-automated by using dedicated scripts, and the standard data files (course coordinates, EM31 ice thickness measurements, and GPS tracks) can be formatted to link easily with a GIS for visualization. We have done this for *Yeti* GPR surveys and could help transfer this capability to USAP survey personnel.

USAP has ongoing needs to conduct sea-ice surveys to support airfields, roads, and staging areas near McMurdo. Additionally, a rover such as *Yeti* can tow other instrument payloads in lightweight, efficient sleds. Example payloads include GPR to map crevasse fields, assess snow roads, and survey land-ice transition areas and radiometers to measure albedo of compacted-snow or white-ice runways. Rover preparation, course planning, and data mapping are all very similar for these payloads, so operator skill and efficiency should improve rapidly. Importantly, systematic autonomous surveys are possible across terrain conditions where the safety of personnel could prevent or limit manual surveys, such as heavily crevassed glaciers and ice sheets. Recognizing these ongoing needs, USAP has funded CRREL to build a second-generation over-snow rover based on *Yeti's* design. This rover (named *SPoTbot*) is nearly complete and should be available for the 2016–17 USAP season.

Therefore, we make the following recommendations to USAP based on this proof-of-concept autonomous survey:

- Assess the needs within USAP for systematic sea-ice surveys, and compare the costs of manual and autonomous methods to address those needs.
- Acquire an EM31 for USAP if sea-ice survey needs justify it. Note that the instrument could also be offered to science projects if their schedules are compatible with those of USAP operations.
- Deploy the Polar rover *SPoTbot* to conduct a variety of surveys, including sea-ice thickness surveys, to gain experience with planning and executing autonomous surveys to support operational needs. *SPoTbot* could also be offered to science projects if their schedules are compatible with those of USAP operations.

- Assess the efficiency gains and cost savings derived from autonomous surveys relative to manual ones to document efficiency improvements resulting from this technology.

By following these recommendations, USAP can implement routine autonomous surveys to support its operations and research activities, leading to substantial cost savings, safer operating environments, and enhanced data collection. These improvements will be important as USAP seeks to reduce costs to support an ever-broadening science program.

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14. ABSTRACT
We conducted an autonomous survey of sea-ice thickness using the Po-lar rover *Yeti* to tow an electromagnetic induction meter over sea ice in McMurdo Sound, Antarctica. This proof-of-concept survey aimed to demonstrate improved efficiency relative to manual surveys routinely conducted to assess the safety of roads and runways constructed on the sea ice. *Yeti* executed the autonomous survey on 11 November 2014. This report describes the methods used, compares the measured ice-thickness profiles with manual borehole measurements, assesses the merits of autonomous surveys relative to manual ones, and describes potential future applications.

15. SUBJECT TERMS
Antarctica, Electromagnetic induction, EM31 electromagnetic meter, EPOLAR, McMurdo Station (Antarctica), NSF, Sea-ice runway, Yeti rover

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