Instruments and Methods

Aircraft-Deployable Ice Observation System (ADIOS) for instrumenting inaccessible glaciers

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ABSTRACT. There remain large regions of scientific interest in the Antarctic that are not instrumented. These include highly dynamic ice streams and glaciers that are difficult or impossible to reach safely because heavy crevassing impedes an overland trek or an aircraft landing. We have developed an alternative strategy for instrumenting these regions: an aerodynamic sensor that can be dropped from an overflying aircraft. During freefall the sensor accelerates to its terminal velocity of 42 m s^{-1} before impacting with the glacier. On impact it partially buries itself in the snow while leaving an antenna mast protruding high above the surface to ensure a long operating life. In this paper, we describe the design and results of testing this aircraft-deployable sensor. Finally we present the initial results of two campaigns to instrument inaccessible regions of Pine Island Glacier, West Antarctica, and Scar Inlet, Antarctic Peninsula, with GPS receivers.

INTRODUCTION

The scientific community has explicitly identified a need to better monitor the contribution of glaciers and ice streams to worldwide sea-level change (e.g. Steffen and others, 2008). It has become increasingly evident that most of the contribution of ice streams and glaciers to sea-level change originates from a few highly dynamic areas, such as the remote Pine Island Glacier, Antarctica (Rignot and others, 2008). Such regions are difficult or impossible to reach by ground or via an aircraft landing (Smith and Stilwell, 2006; Buckley, 2007).

Remote sensing can provide some ice motion and flow data in these areas, but such techniques are restricted by poor temporal resolution (Park and others, 2010) and often a lack of stable tracking features (Howat and others, 2005). An alternative is to measure the ice motion and flow data from GPS receivers installed on the surface. Thus some method of instrumenting highly dynamic glaciers with GPS receivers is required.

Concept outline

Helicopters have been used to instrument areas where crevassing prevents a fixed-wing aircraft from landing. However, their limited range and payload capacity make them unsuitable for any operations beyond the proximity of a large supporting infrastructure. If fixed-wing aircraft had the same ability to instrument crevassed regions, then the advantages of their increased range, availability and operation costs would be significant.

One solution is to adapt the sonobuoy concept to create an Aircraft-Deployable Ice Observation System (ADIOS). Instead of dropping sonobuoy sensors into oceans, we intend to drop a network of ADIOS sensors onto ice streams.

The obstacles to installing sensors on glaciers apply equally to the challenge of retrieving their data locally. Instead ADIOS must transmit its data to remote servers via a satellite link. Unlike a sonobuoy, which can rely on flotation to ensure its communications antenna is vertical and persists above the surface, this sensor must have a controlled impact angle and speed in order to set its ultimate orientation and depth within the snow. These criteria, in conjunction with local snow accumulation rates, will determine the upper limit of the lifetime of the ADIOS network.

DESIGN AND METHODS

The requirement for ADIOS to be deployable from an aircraft necessarily places certain constraints on its design.

Design constraints

In order to minimize costly and time-intensive changes to the aircraft platform, ADIOS is deployed from a standard sonobuoy launch tube mounted 45° to the aircraft floor. This limited the diameter of the device at the point of deployment to that of the tube. Also the clearance between the launch tube and the top of the aircraft cabin constrained the length of any component of ADIOS prior to being installed in the launch tube (Fig. 1).

As these devices are dropped in inaccessible regions, they need to be considered disposable, placing constraints on both the cost and the environmental impact of the design. Further, it is not possible to return to collect data from the ADIOS network, so the devices must periodically transmit data back via a remote server.

Once snow accumulation buries the communications antenna, ADIOS will no longer operate. Thus, the device needs to include some form of mast, supporting the antenna above the surface for as long as possible. Further, the precise density and viscosity of the snow in the target area are not known prior to deployment, so the device needs to be resilient to a large range of snow conditions.

The antenna mast must be nearly vertical, in order to ensure both the maximum height and the optimum orientation of the antenna. This in turn means ADIOS has to be dropped from a sufficient height so that its trajectory is nearly vertical before impact. Also the aerodynamics needs

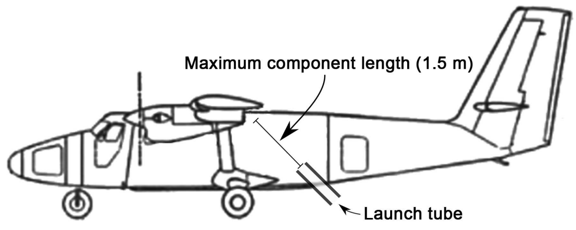

Fig. 1. Twin Otter aircraft fitted with sonobuoy launch tube.

to be statically and dynamically stable – the angle of attack of the device cannot be oscillating prior to impact.

The aforementioned size constraints also limit the power solution. An effective solar panel or wind turbine will not fit through the launch tube, so the payload needs to be powered by a primary battery. In turn, this constrains the electronics to consist of only low-power components. The capacity of the power source and the power consumption of the payload will be a limit on the effective duration of the operation of the device.

The device has to impact the glacier with sufficient force to bury itself even in dense snow conditions. This in turn means ADIOS rapidly decelerates after impact, and the payload must be resilient to the deceleration forces and survive the impact intact.

In order to ensure ADIOS is safe to deploy from an airborne platform, the trajectory of the device after deployment needs to maximize separation from the aircraft as fast as possible. The slowest operational speed of the aircraft used in this programme is 50 m s^{-1}, so that the device is dropped into an airstream of an equivalent velocity. Thus,

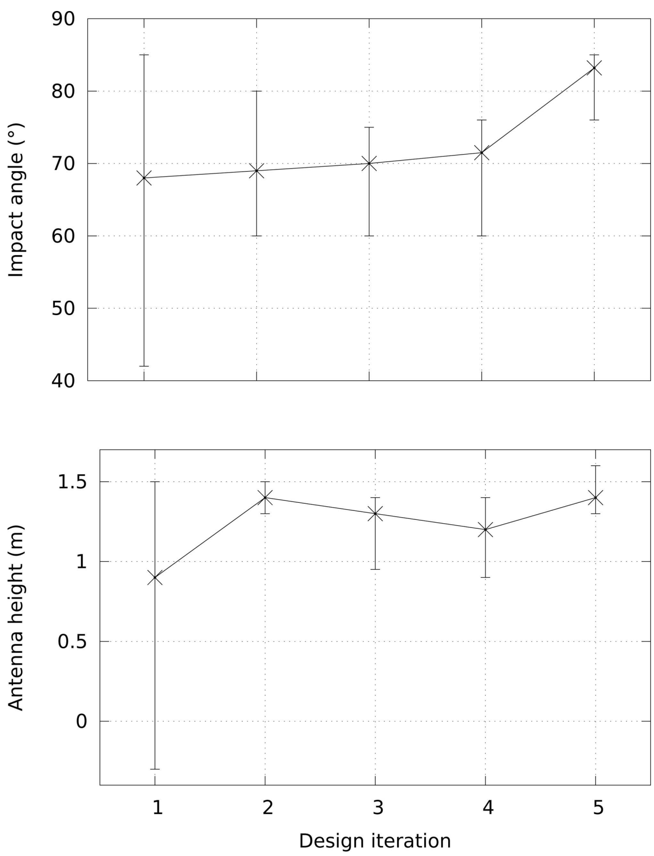

Fig. 2. Design performance over five sets of trial and error.

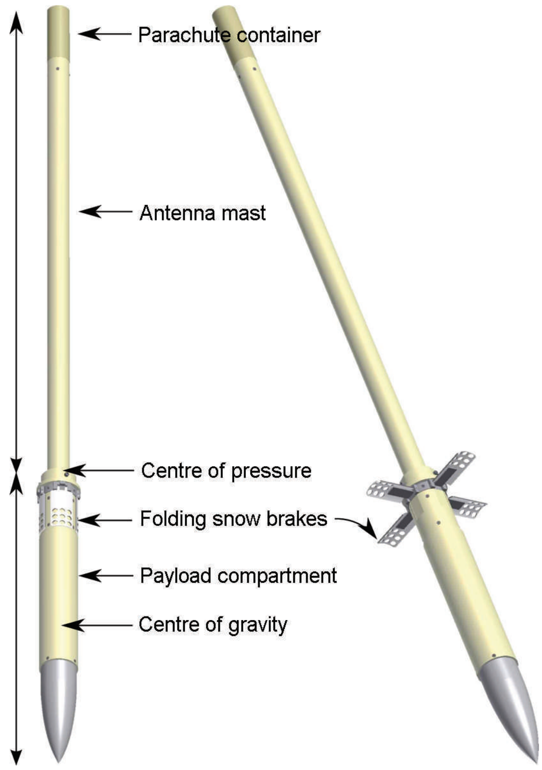

Fig. 3. ADIOS design.

while the device is within proximity of the aircraft it must have a small aerodynamic profile in order to prevent the airstream, or turbulence under the aircraft, from deflecting ADIOS back towards the aircraft.

Design testing

Over the last 2 years we have conducted design trials in a vertical wind tunnel and from flights local to two Antarctic bases. These trials were used primarily to improve the design stability and the depth to which each ADIOS unit buried itself. The objective was to have each device impact the glacier at ~90°, and for its antenna mast to protrude 1.5 m above the surface. Figure 2 shows the results of these trials in different snow conditions. Simple designs (e.g. design iteration 1 in Fig. 2) were tested but proved unstable and insufficiently robust at different snow densities. By refining the parachute design, fin design and centre of gravity we were able to overcome both issues.

Design solution

The final ADIOS design has an aerodynamically stable shape (Fig. 3) and was fitted with a small parachute. The device consists of two separable components that are assembled inside the aircraft, with the first component already loaded in the launch tube. This allows us to deploy a device longer than the 1.5 m limitation due to aircraft (Twin Otter) cabin size (Fig. 1).

Case design

The ADIOS is 2.5 m long and consists of a slender 1.5 m mast, a wider payload compartment and a solid aluminium nose cone. The mast and payload compartment are manufactured from polypropylene, chosen for its impact strength in cold environments. The remaining components are manufactured from aluminium.

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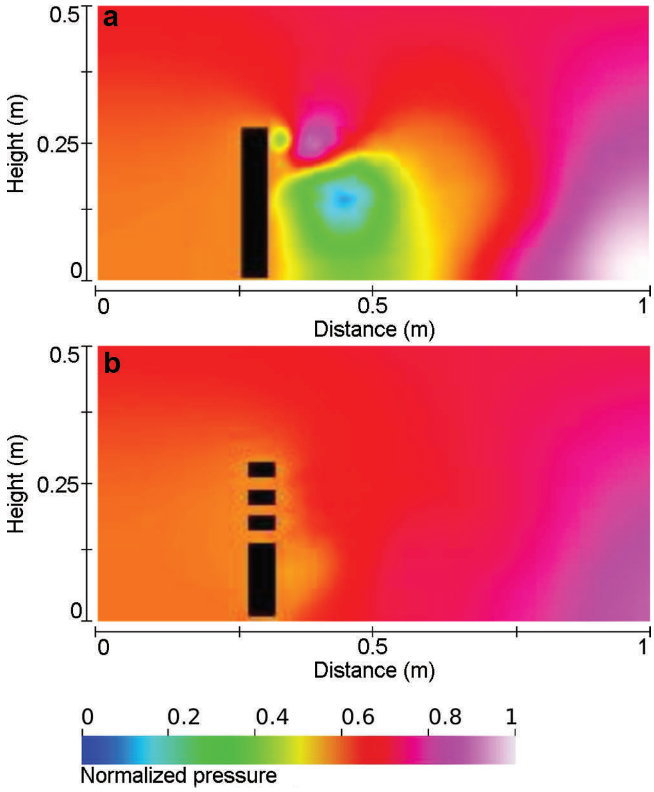

Fig. 4. Results of finite-element modelling the aerodynamics of components of ADIOS. Normalized air pressure around (a) a solid snow brake and (b) a geometrically porous snow brake. The direction of airflow was left to right.

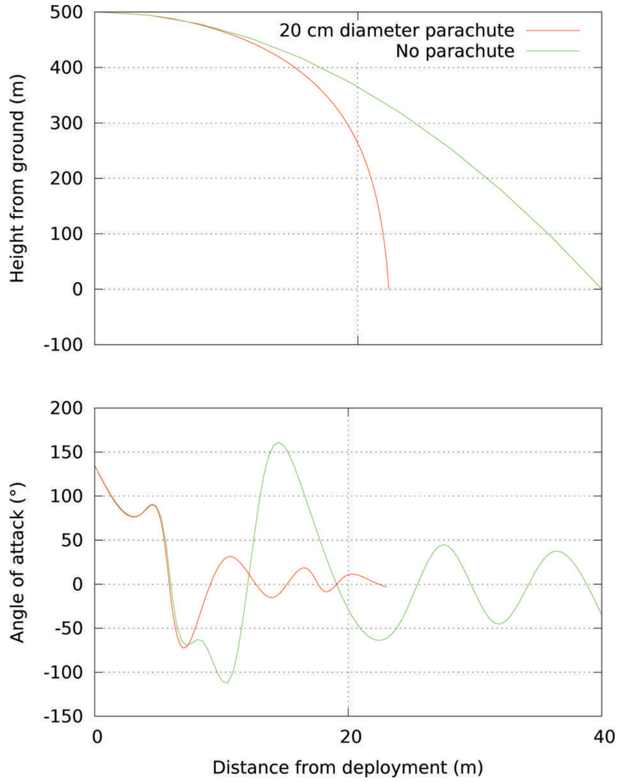

Fig. 5. Device trajectory and stability data from experiments.

The aerodynamic centre of pressure (CoP) is the point on the body where the pressure field can be replaced with a single force vector with no moment, effectively the point about which the body will pivot as it falls. If the centre of gravity (CoG) of ADIOS is behind the CoP, the device will fall backwards. If the CoG is above the CoP, the device will rotate throughout its descent. The greater the separation of the CoG from the CoP, the greater the aerodynamic stability of the device. For this reason, the nose cone is made of solid aluminium, increasing its weight and the separation of the CoG from the CoP. Further, the added weight increases the terminal velocity and kinetic energy of ADIOS at the point of impact, and thus increases its penetration depth in dense snow conditions.

In order to ensure that, after impacting with the snow, the payload compartment is subsurface while leaving the antenna mast protruding above the surface, four snow brakes are mounted at the top of the compartment. These effectively increase the surface area by a factor of four, and correspondingly its drag in the snow when the device is buried to 1 m depth. These snow brakes fold forward and fasten closed during deployment, so that they fit through the launch tube and their aerodynamic effects are minimized while close to the aircraft. When the device is clear of the aircraft the snow brakes are released and locked open. The size and shape of these brakes are a trade-off between their adverse aerodynamic qualities and their ability to stop the device burying to too great a depth.

Because the surface of each brake is orthogonal to the airstream, a region of low-pressure air is created immediately behind each of them. A Navier–Stokes model of this airstream (viscosity = 0.00001 $\mathrm{N\,s\,m^{-2}}$, density = 1.0 $\mathrm{kg\,m^{-3}}$) was solved with the open-source software Elmer, showing the creation of this region of low-pressure air behind a snow brake (Fig. 4a). Small variations in the angle between the airstream and the ADIOS surface caused these low-pressure regions to alternate from brake to brake, which in turn caused ADIOS to oscillate underneath its parachute. Experiments showed that oscillations about a 40° arc could be sustained by this effect. We reduced the size and intensity of the low-pressure region, and increased its stability, by making each brake geometrically porous (Fig. 4b). Further experiments showed that this reduced the size of the arc about which ADIOS oscillated to $<10°$.

Another method we used to reduce the adverse aerodynamic qualities of the brake was to locate the brakes close to the CoP, thus reducing their moment.

Parachute design

Without some form of stabilizing drag, during freefall ADIOS would have oscillated about its CoP and the horizontal velocity of the device would have been largely sustained. Both effects would have prevented the device from impacting with the ground at 90°. Figure 5 compares the trajectory and stability of two designs during deployment tests. The angle of attack and trajectory were measured from video footage from ground and airborne observers.

While a parachute can dampen some oscillation modes, it can also induce different modes of oscillation. At the point when the parachute opened, ADIOS had a vertical velocity of 5 $\mathrm{m\,s^{-1}}$ and a horizontal velocity near to 50 $\mathrm{m\,s^{-1}}$. The parachute opened rapidly and exerted a sudden 150 N force opposing this horizontal motion. This induced the device to both swing underneath the parachute and start rotating

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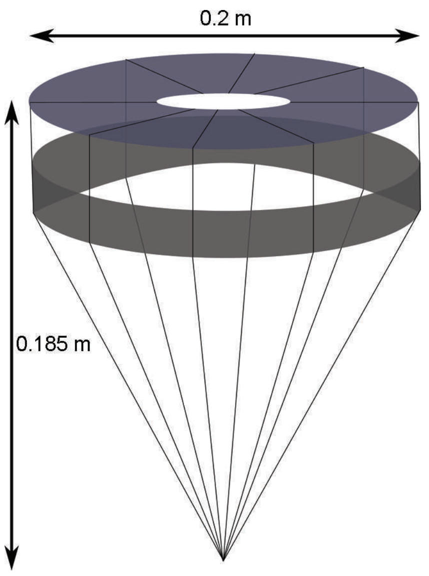

Fig. 6. Disk Gap Band parachute design.

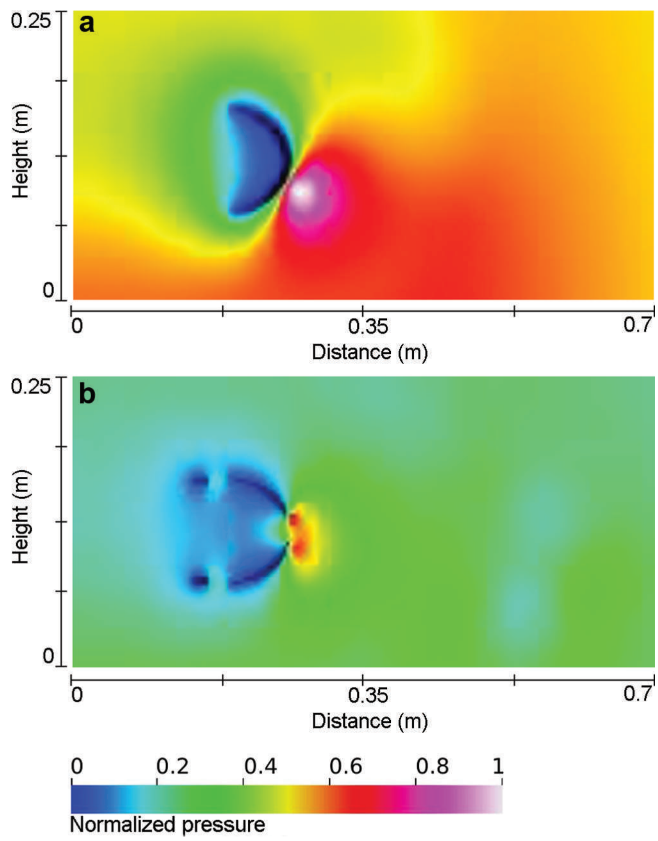

Fig. 7. Results of finite-element modelling the aerodynamics of components of ADIOS. Normalized air pressure around (a) a solid flat circular parachute and (b) a Disk Gap Band parachute. The direction of airflow was left to right.

about its CoG. Experiments showed these oscillations were damped within 10 s of freefall.

Another parachute oscillation mode was caused by irregular and fluctuating airflow conditions around and through the surface of the canopy. In the case of solid flat circular parachutes, the airflow separated from the leading edge of the hemisphere in alternating vortices. This alternating flow separation caused large differences in the pressure differential on opposite sides of the skirt of the canopy (Fig. 7a), which in turn produced large destabilizing normal forces and large oscillation amplitudes (Guglieri, 1992). Dynamic stability was achieved by controlling this airflow with a more advanced canopy shape.

We used a Disk Gap Band parachute canopy shape (Fig. 6). This parachute design was first proposed for meteorological rockets (Eckstrom and Murrow, 1966) and later deployed as part of the Mars Viking program (Moog and others, 1973). The roof of the canopy is formed from a flat sheet, and the skirt of the canopy is cylindrical and thus extended perpendicularly from the disk areas to form a band. The right-angle change in shape from the band to the disk portion of the canopy provides a discontinuity in the surface shape and causes the airflow to separate more uniformly around the canopy (Fig. 7b). Also, since the canopy is geometrically porous, more air passes through the canopy and less air flows around the canopy skirt; hence the vortices shed at the skirt are weaker. By adjusting the ratio of gap width to canopy surface area, the flow of air exiting the interior of the canopy is controlled sufficiently to maximize the drag of the parachute while maintaining the required degree of stability (Eckstrom and Murrow, 1966). Various ratios of gap width, canopy diameter and skirt size have been proposed (Gillis, 1973; Fallon, 1997; Cruz and others, 2003). We used wind tunnels to test four parachute design variations, in order to determine which most effectively stabilized ADIOS.

Another instability mode is caused by interactions between the parachute and the wake from the end of the antenna mast. This effect is reduced by using a geometrically porous canopy and attaching it far behind the payload. Further wind-tunnel tests were used to determine the optimum distance to attach the parachute from the end of the ADIOS antenna tube.

Prior to deployment, the parachute is packed inside a container that fits around the top of the antenna mast. This container prevents the parachute from opening, and protects the antenna during deployment through the sonobuoy launch tube. The container is attached to a cord which in turn is attached to a fixed point inside the aircraft. When ADIOS is 2 m clear of the aircraft, the cord pulls the container off the top of the mast, allowing the parachute to inflate.

Most of the test flights and ADIOS deployments in the Antarctic were to determine the necessary parachute size for the device, in order for it to achieve a stable trajectory and sufficient terminal velocity to bury itself to the correct depth in different snow conditions. The relationship between parachute size and device terminal velocity is governed by

$$V_\infty = \sqrt{\frac{2mg}{\rho A C_\mathrm{d}}} \tag{1}$$

where V_∞ is the terminal velocity of ADIOS, m is the mass of the device, g is the acceleration due to gravity, C_d is the drag coefficient of the parachute, ρ is the density of air and A is the effective surface area of the parachute.

From Eqn (1) the terminal velocity of ADIOS is 42 m s^{-1}. Later experiments in the wind tunnel and drop tests confirmed this result.

The parachutes are manufactured from kevlar and nylon. These materials were chosen for their light weight and small environmental impact.

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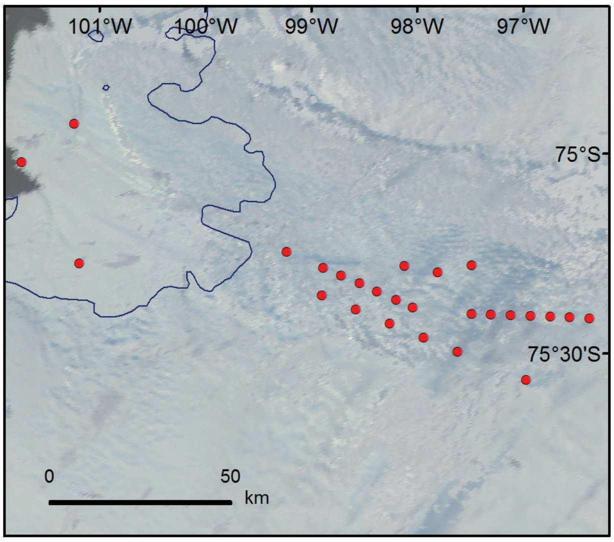

Fig. 8. Operational ADIOS-GPS sensors on Pine Island Glacier in 2013. Blue line is the grounding line (Fretwell and others, 2013).

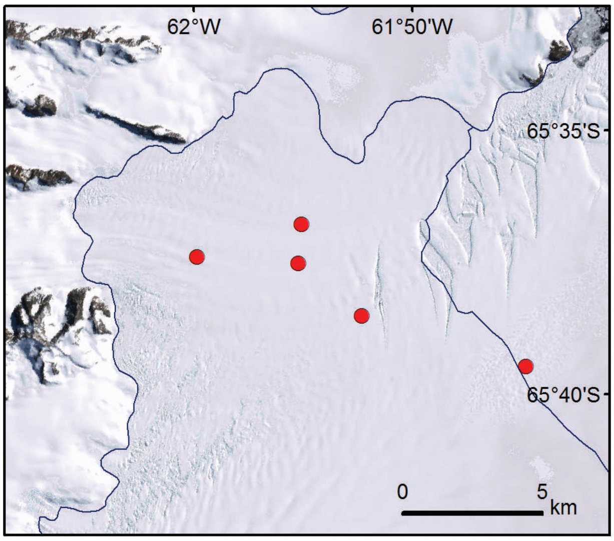

Fig. 9. Operational ADIOS-GPS sensors on Scar Inlet in 2013.

Payload packaging

On impact with the snow surface, the device rapidly decelerates. The payload needs to survive this impact, and must be resilient to a range of different snow densities. For the device to decelerate on impact from its terminal velocity to stationary within the 1 m body length, the payload needs to withstand a minimum of a 90*G* deceleration. In less dense snow the snow brakes perform much of the deceleration, typically within a 10 cm depth. Under those conditions the payload must withstand a minimum of a 900*G* deceleration.

Our design uses a polyethylene cushion to protect the electronics payload, and a combination of polyethylene and a spring that cushion the battery up to a 1200*G* deceleration. This was verified by repeated test drops in different snow conditions.

Environmental impact

In order to reduce the environmental impact of ADIOS we used non-toxic, non-bioaccumulating materials such as polypropylene (Environment Canada, 2008), biodegradable nylon and ultraviolet-degradable kevlar. Also by designing the GPS payload to have a low power consumption, we are able to minimize the size of the necessary battery pack.

CASE STUDY: DEPLOYMENT OF TWO ADIOS-GPS NETWORKS

During the 2012/13 austral summer we deployed 43 ADIOS units fitted with a GPS payload (ADIOS-GPS) on Pine Island Glacier, upstream of the grounding line, and Scar Inlet.

ADIOS-GPS payload

The ADIOS units were fitted with a low-power single-band GPS receiver. Position fixes were taken six times a day. These data were combined with measurements of the GPS accuracy, unit temperature and battery life. The resulting data packet was compressed and transmitted over the iridium satellite network in a short-burst data packet format.

The module is powered by a lithium sodium chloride battery pack formed from eight D-cells. This chemistry was chosen for its low power and high capacity in cold operating conditions. The battery pack is sufficient to power each ADIOS-GPS unit for 2 years.

The ADIOS payload compartment volume is 3.5×10^3 mm^{-3}, and the weight of the potential payload is largely unconstrained. The ADIOS-GPS payload does not fully utilize the capacity of the ADIOS payload compartment, so there is potential for future payload upgrades.

Results

Each sensor impacted, on average, 190 m from its target. Of the 37 ADIOS-GPS units we deployed on Pine Island Glacier, 26 survived the impact and started operating (Fig. 8). Of the six ADIOS-GPS units we deployed on Scar Inlet, five survived the impact and started operating (Fig. 9). Both target areas were heavily crevassed (Fig. 10), so it is likely the majority of the failed units hit a crevasse; however, subsequent attempts to visually confirm this from an aircraft failed. A further five sensors have since failed and 26 are still operational (Fig. 11).

The average accumulation rate on Pine Island Glacier (assuming $\rho = 500$ kg m^{-3}) is 0.87 m a^{-1} (Arthern and others, 2006), and the antenna of each device is ~1.5 m above the surface, so we expect to achieve up to 2 years of operation from the network of ADIOS-GPS sensors on Pine Island Glacier. Accumulation rates on Scar Inlet are much lower, so the duration of the network in operation there will be limited by the lifetime of the battery in each sensor.

Fig. 10. Pine Island Glacier. The target area for the sensors was heavily crevassed.

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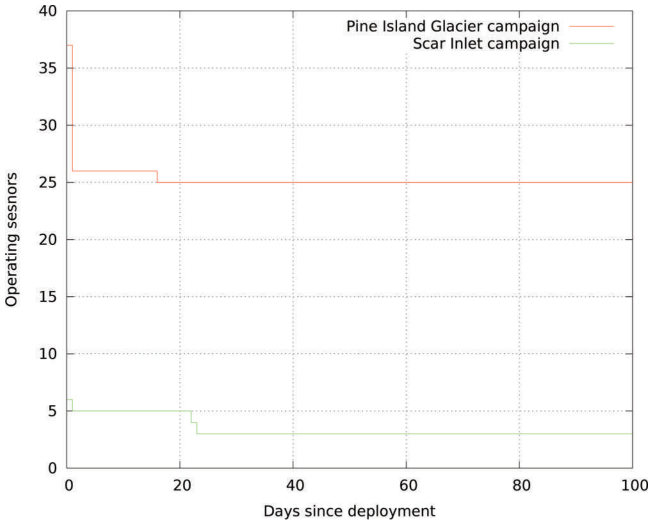

Fig. 11. Lifetime of the 43 ADIOS-GPS sensors on Pine Island Glacier and Scar Inlet.

CONCLUSION AND OUTLOOK

We have developed and tested a sensor delivery package and strategy that can be used to instrument otherwise inaccessible glaciers from an aircraft. This strategy was demonstrated by successfully instrumenting previously inaccessible regions of Pine Island Glacier and Scar Inlet.

This ADIOS design has the potential to open up other regions of the Antarctic and Arctic for instrumentation, where terrestrial access has not previously been possible. However, there are limitations on where future sensors can be deployed:

ADIOS is not capable of penetrating thick layers of ice.

Areas with a high accumulation rate will limit the effective lifetime of the sensor.

ADIOS is not suitable for deployment in areas with a snowpack <1 m deep.

There are also limitations on the size of the payload that can be deployed. Despite this, we anticipate fitting alternate payloads to the device, such as small automatic weather stations, low-power magnetometers and more accurate, dual-band GPS sensors. We have already test-deployed a dual-band GPS sensor, and intend to deploy more of these in 2014.

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