Instruments and Methods

A wireless multi-sensor subglacial probe: design and preliminary results

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ABSTRACT. This paper introduces a new way to investigate in situ processes, the wireless multi-sensor probe, as part of an environmental sensor network. Instruments are housed within a 'probe' which can move freely and so behave like a clast. These were deployed in the ice and till at Briksdalsbreen, Norway. The sensors measure temperature, resistivity, case stress, tilt angle and water pressure and send their data to a base station on the glacier surface via radio links. These data are then forwarded by radio to a reference station with mains power 2.5 km away, from where they are sent to a web server in the UK. The system deployed during 2004/05 was very successful and a total of 859 probe days worth of data from the ice and till were collected, along with GPS, weather and diagnostic data about the system.

INTRODUCTION

An understanding of subglacial processes is vital to understanding glacier dynamics, as it has been suggested that both modern and ancient glaciers are controlled by the nature of the bed (Boulton and Jones, 1979; Alley and others, 1986) and subglacial deformation has been recorded at many modern glaciers by in situ process studies (Murray, 1997; Fischer and Clarke, 2001) and proglacial foreland studies (Hart and Rose, 2001).

One of the major developments over the past 20 years in glaciology has been the use of subglacial instrumentation to study subglacial processes (for a summary see Boulton and others, 2001). Most studies use tiltmeters to investigate whether the till is actively shearing (Iverson and others, 1995), ploughmeters to measure sediment strength (Fischer and Clarke, 1994) and drag spools to measure sliding velocity (Blake and others, 1994). These studies have demonstrated that both till deformation and basal sliding occur beneath the glacier, and that changes in pore-water pressure and sediment strength fluctuate rapidly on very short timescales.

However, all these studies have an intrinsic problem, in that the instruments are connected by wires to a data logger at the glacier surface, and although spare cable is often left to reduce movement disturbance, the instruments cannot move freely. The use of loggers also makes data and maintenance access intermittent.

The aim of the GlacsWeb project was to construct a wire-free autonomous probe which was part of a wireless sensor network (Martinez and others, 2004). The sensors were encased in a probe that was designed to be able to replicate natural clast behaviour. These were inserted into the ice and the till and were able to send information back to the surface via radio communications, which could then be accessed in near-real time via the internet.

Harrison and others (2004) also developed probes with a wireless system using very low-frequency (500 Hz) radio, which they inserted into the subglacial sediment at Black Rapids Glacier, Alaska, USA, via a hole drilled in the till with a very heavy slide hammer. Their system comprised three large (61 cm long) probes at one location, with data collected a few metres away by a wired receiver and accessed by manual logger downloads. The system demonstrated that subglacial wireless sensing was possible, though not without difficulties.

The GlacsWeb system was installed at Briksdalsbreen in southern Norway (Fig. 1a) because the foreland showed potential evidence for the presence of a deforming bed (push moraines and flutes in fine-grained till; Hart, 2006), as well as good access and communications systems. The latter included GSM (global system for mobile) telephone coverage on the glacier and a local (2.5 km away) ISDN (integrated services digital network) telephone connection, which allows the transmission of data to the UK.

In this paper, we outline the three elements of the system (probes, base station and reference station), discuss some of the challenges in developing such a system and provide a summary of the preliminary results.

FIELD SITE

The study sites on the glacier were chosen where the glacier was flat and crevasse-free with safe access (Fig. 1b). The glacier and foreland were mapped with a Topcon differential GPS (global positioning system) (DGPS) and the thickness of the glacier was determined from measured borehole depths, drilled with a Kärcher HD100DE car wash, and from a ground-penetrating radar (GPR) survey. For the latter, an EKKO 100 GPR with a 1000 V transmitter was used, with a common-offset survey using 50 MHz antennas on a grid pattern with a 2 m antenna spacing and a 0.5 m sampling interval. In addition, the velocity of radar in ice was found to be 0.16 m ns^{-1} taken from a common-midpoint (CMP) survey. The boreholes and till were examined with a

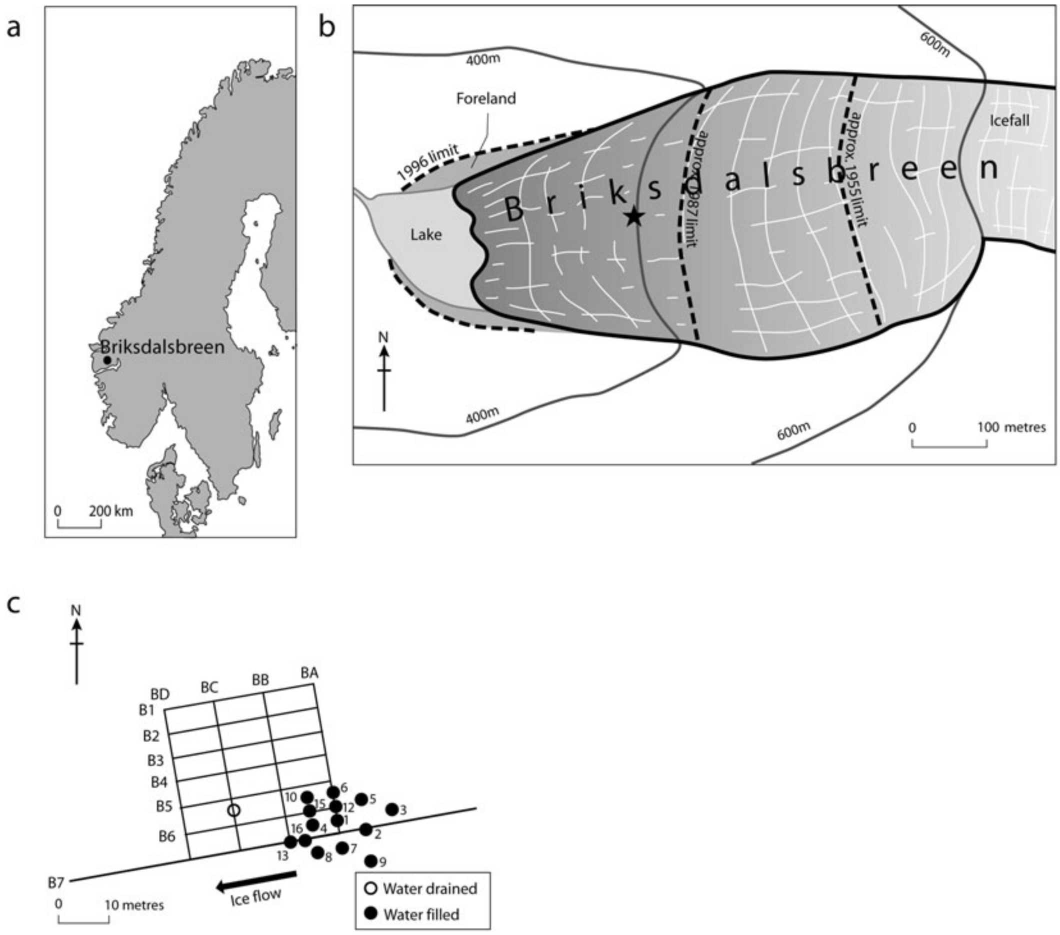

Fig. 1. (a) The location of Briksdalsbreen in southern Norway. (b) Map of the glacier and foreland with site locations marked (site A = 2003; site B = 2004). (c) GPR transects and boreholes shown.

custom-made infrared (900 nm) camera. In addition, a till sampler was attached to a subglacial hammer (Blake and others, 1992) to verify the presence or absence of till.

Although the borehole deviation from the vertical was unconstrained, the measured depths of the boreholes (measured with a marked drill pipe and the camera cable) were very close to the calculated depths from the radar taken in the same area. This similarity of results allows us to interpret the glacier depth in the survey area to range from 62 to 71 m. The details of the boreholes are summarized in Table 1.

SYSTEM OVERVIEW

A general system overview is shown in Figure 2. Sensor probes are inserted into the ice or till, and send their information to a base station on the ice surface; this then sends its information to a fixed reference station. The reference station is the gateway for transferring data and allows remote control or monitoring of the entire system if necessary.

There were a number of factors that influenced the design of the system:

Radio frequency. Radio-wave propagation in pure ice depends on relative permittivity and dielectric loss factor. The dielectric constant of ice at 0°C is approximately 3.17 (Glen and Paren, 1975) and the absorption of radio over 100 m of ice at –1°C at 100–1000 MHz is less than 10 dB (Evans and Smith, 1969). Budd and others (1970) and Dowdeswell and Evans (2004) argue there is no significant loss by absorption up to frequencies of 800 MHz. However, glaciers contain sediment, water and air bubbles which significantly affect radio transmission.

Probe size. The probes needed to be small and inexpensive to allow as many as possible to be constructed and inserted into the ice and subglacial till. A hot-water drill was used to drill the holes, so the hole diameter sets a maximum size for the probes. The probes were also designed to be elliptical in shape, so their movement could be compared with theoretical studies of clast behaviour in a viscous medium (e.g. Jeffery, 1922; Glen and others, 1957).

Power management. The probes need sufficient power to function for a year or more. Unlike the majority of environmental monitoring situations, there is no alternative (e.g. solar) power source under the ice.

In order to satisfy both miniaturization and frequency requirements, the radio frequency has to be a compromise between antenna size and transmission loss. Higher-frequency systems allow shorter antennas but at the expense of greater propagation losses (shorter communication range and/or higher transmission power), and conversely. In addition, the greatest radio loss occurs in the upper part of

Table 1. Borehole characteristics

Borehole	Borehole depth m	Till present*	Probe No.	Probe depth m	Initial transmission distance m	Estimated maximum working transmission distance m	Probe in till or ice
1	70	v	7	70	36	36.26	till
2	70	n	4	19	19	19	ice
3	~71	n	–	–	–	–	–
4	69	s, v	2	69	34	–	till
			Transceiver	35			
5	70	c, v	–	–	–	–	–
6	68	c, v, s	–	–	–	–	–
7	75	v	6	72	37	–	ice
8	68	c, v	3	68	33	–	clast
9	~70	v	–	–	–	–	–
10	68	n	1	–	37	–	ice
11	30	n	–	–	–	–	–
12	66	s, v	–	–	–	–	–
13	69	v	8	69	33	33.6	till
14	63	v	–	–	–	–	–
15	62	v	–	–	–	–	–
16	68	c, v	5	68	33	33.4	till

*s: till sample taken; v: till seen on video; c: clast seen at base.

the glacier where there is more liquid water. To avoid this, a transceiver was hung beneath the ice surface with a long serial/power cable (the method to determine the optimal depth for the transceiver is discussed below). To facilitate power requirements, the probes would remain 'asleep' for most of the time, only 'wake up' and record their data six times a day, and transmit these data once a day to the base station on the glacier surface.

The system described here was able to measure probes' tilt angle, water pressure, resistivity, temperature, case stress and battery voltage, as well as the base station's tilt angle, temperature and battery voltage, plus a GPS recording of the location of the base station, the weather at the base station and data from a 'traditional wired' tiltmeter and ploughmeter inserted into the till.

Probes

The probes are custom-made and comprise a microcontroller, storage, sensors, radio communications system and power controller and supply held within a bespoke case (Fig. 3; Table 2). The probe's circuitry remains largely unpowered until they are 'woken' by their real-time clock.

The probes contained a PIC (peripheral interface controller) 8-bit microcontroller, responsible for reading and storing sensor data, configuring the real-time clock and interpreting commands. Each probe had one 1.7 MPa pressure sensor, two dual-axis 180° micro-electromechanical system (MEMS) tilt angle sensors and a temperature sensor. There were two additional bolts through the case to measure external resistivity, and strain gauges to measure the stress on the case. The probes could not contain a compass because of the metals within the probes. The *x* and *y* tilt sensors measure the angle of tilt from the vertical (0° *x* tilt, 0° *y* tilt represents the probe standing vertically). The analogue values of the pressure and tilt angle sensors were converted on board by the microcontroller; the temperature sensor was accessed via the inter-integrated communication (I^2C) protocol (connector bus). This protocol also accesses the real-time clock and 64 KB FlashROM, where a back-up of about 2 years of data can be stored.

The radio communications system included conventional helical antennas with a power amplifier to boost the 10 mW output to around 100 mW. A custom packet-based protocol (a basic unit of information carriage) with error detection was devised for communication with the base station.

The probes were powered by lithium thionyl chloride cells chosen for their high capacity-to-volume ratio and good characteristics at low temperatures. This consisted of six half AA sized cells providing 6 A h (ampere-hours).

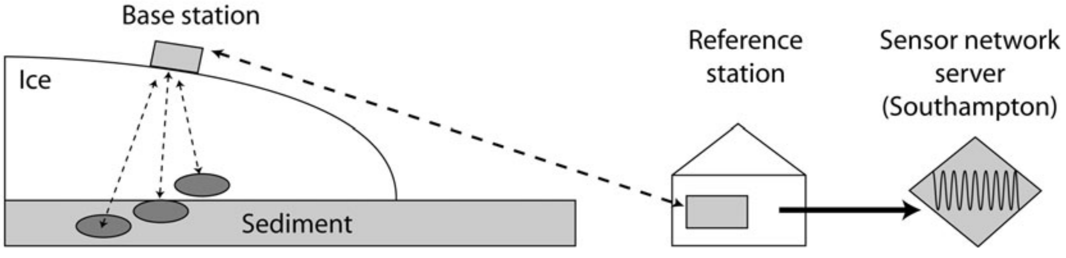

Fig. 2. Overall system diagram.

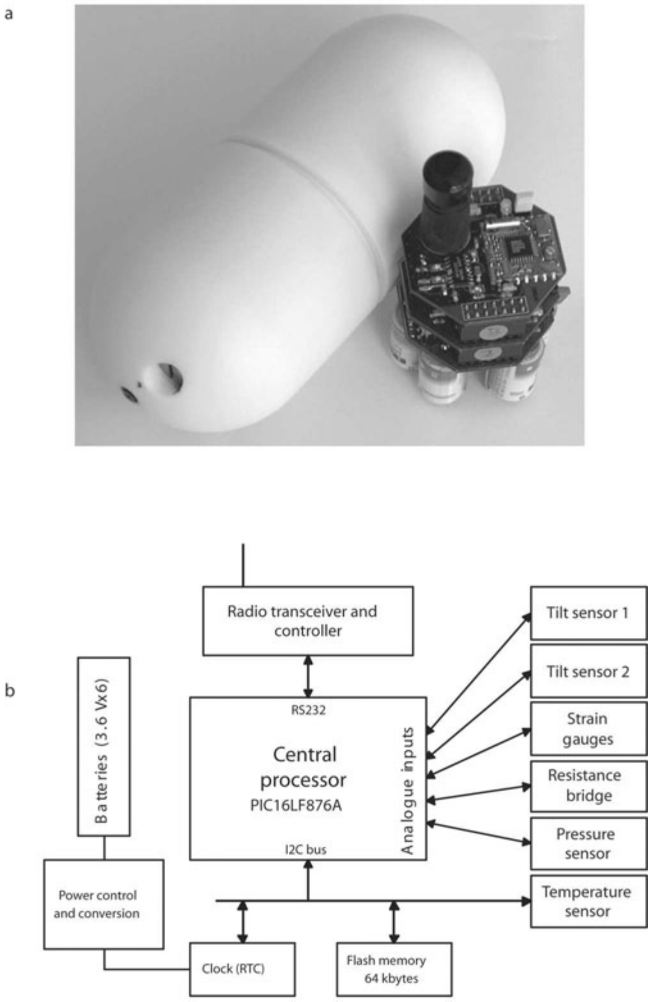

Fig. 3. Probes: (a) photograph of 16 cm long probe (showing the resistivity bolts and pressure sensors at the end); (b) schematic.

The electronics and sensors were enclosed in a polyester cylindrical capsule composed of two halves and sealed with epoxy resin (Fig. 3a). This probe was 16 cm long, with an axial ratio of 2.9 : 1. The probes were tested in a pressurized tank at the National Oceanography Centre, Southampton, up to 100 m of water pressure.

In sleep mode, the probes only consume 9 μA and when powered 4.2 mA (with the transceiver off) at 3.6 V. Battery voltage is also measured each day as a vital diagnostic. Once collected, the data are stored in a ring buffer fashion (64 KB) in the FlashROM until they are accessed. The oldest data are overwritten by the newest only when the entire memory is full. This allows the data to be preserved even if communications fail for many months.

Base station

The base station is responsible for fetching data from the probes, recording local data, a GPS file and weather station data. It also transmits data either via radio down the valley or by mobile-phone text messages. As size is not critically important, it has two large 12 V lead acid batteries with 96 A h capacity in total, as well as a 15 W solar panel and a 60 W wind generator (Rutland 503). A pyramidal tripod was designed to hold the antennas and sensors; this was tethered to the ice with an anchor (15 m down a borehole) and rocks on the base (Fig. 4a). The customized base station comprised a central processing unit (CPU), storage, sensors, radio communications system and power controller (Fig. 4b; Table 2).

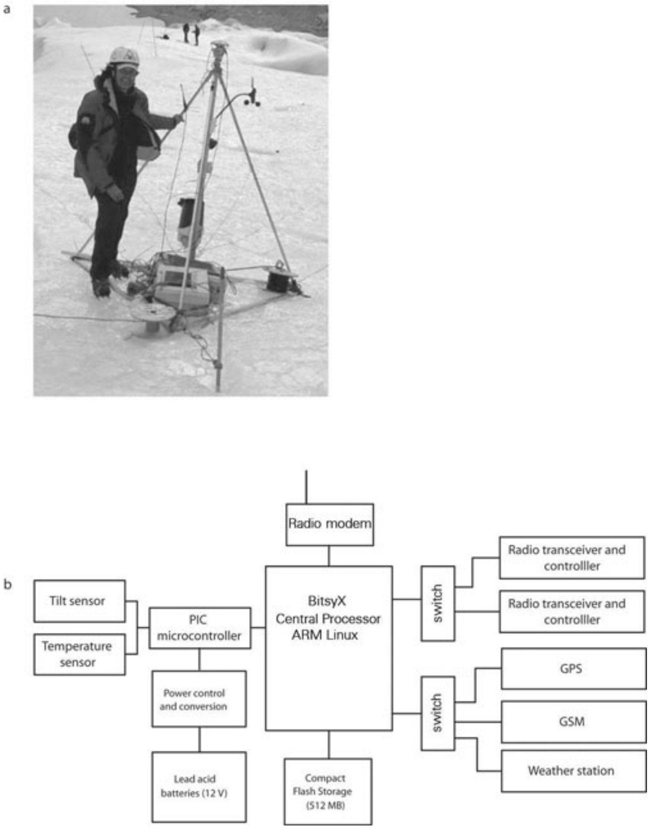

Fig. 4. Base station: (a) photograph; (b) schematic.

The base station is controlled by a StrongARM-based board (BitsyX) running Linux, allowing remote access and standard software to be used. There are a series of peripherals attached to the processor board through a custom interface board. Sensors measure the local conditions of the base station (tilt angle, temperature and battery voltage), and wired tiltmeters and ploughmeters were inserted into the till. These were connected via a PIC. The GPS, weather and GSM systems were connected via serial connections. The storage system is a CompactFlash card.

A 500 mW radio modem provided a 9600 baud (signals per second) link 2.5 km down-valley to the reference station personal computer (PC). Robust communications are essential to prevent radio noise from interfering with system operations and to maintain data integrity. A GSM modem allowed probe data to be sent directly to the UK server via text messages (SMS) if the long-range link was not functioning.

Reference station

The reference station is a mains-powered mini-ITX PC running Linux, located in a building in the valley (Melkevoll Campsite Office, approximately 2.5 km from the glacier). It was connected to the base station via the radio modem, and periodically to the internet via ISDN. It is the position reference point and records a GPS file daily. This PC relays the data from the probes and base station to a data server in Southampton on a daily basis and archives the data on disk as a back-up.

Table 2. Details of the system

	Probes	Base station
Microcontroller/ CPU	PIC16LF876A	StrongARM BitsyX
Storage	64 KB FlashROM	CompactFlash card
Sensors	Tilt angle Strain gauge Pressure sensor Temperature Resistivity	Tilt angle Temperature Tilt angle cells Ploughmeter GPS Weather station
Communication	433 MHz helical antenna	433 MHz helical antenna 468 MHz radio modem GSM phone
Power controller and supply	6 × 0.5 AA lithium thionyl chloride cells	Lead acid batteries 10 W solar panel 60 W wind generator Switch mode regulators
Case	Polyester – push closed	Pelican case

System

The real-time clocks in the base station and probes control the timing of data collection and transmission according to a time schedule (Table 3). At the end of each period, the probe and base station configure their clocks to the next ‘wake-up’ time before ‘sleeping’. Probes only record data from their sensors during data log periods. During the communication period, they enable their radio transceivers for a fixed duration after recording their sensors. The base station powers up during this period and reads its own sensors, broadcasts the system time and requests undelivered sensor readings from the probes. A communication window opens for a short time once the systems are idle and it is possible to log in from the UK. The base station and reference station also ‘wake up’ during the GPS log period to read GPS data. All the data that have been recorded over the day are transferred to the data server in Southampton during the transfer period.

Table 3. Communication sequence

Time	Probe	Base station	Reference station
0000 h	Data log		
0300 h		GPS log	GPS log
0400 h	Data log		
0800 h	Data log		
	Data log		
1200 h	Communications	Communications	Communications
1600 h	Data log		
1900 h			Transfer
2000 h	Data log		

It became increasingly clear that diagnostic information should be built into the system and data because of the system complexity and the need to understand failures. A daily log file was sent to the UK with extra status information including a log of all probe communications, battery voltage (probe and base station) and base station sensors (tilt angle). This provided valuable information, and problems in the reference station could be solved by remote reprogramming. However, it was necessary to travel to the site in the spring and autumn in order to install replacement parts and upgrades as well as to check the system for weather damage.

SUMMARY OF THE RESULTS

Prior to inserting the probes, the subglacial environment was surveyed by GPR, borehole drilling, till sampling and borehole video in order to find the best locations for probe deployment. Areas with subglacial channels needed to be avoided, and areas with thick till preferentially chosen.

Data from the GPR survey from 2003 and 2004 were used to determine the appropriate depth for the transceiver. The surface zone is characterized by high-amplitude reflectors which suggest high water content at the glacier surface (Fig. 5a). In order to locate the depth of this highly reflective zone, a threshold was determined by manual

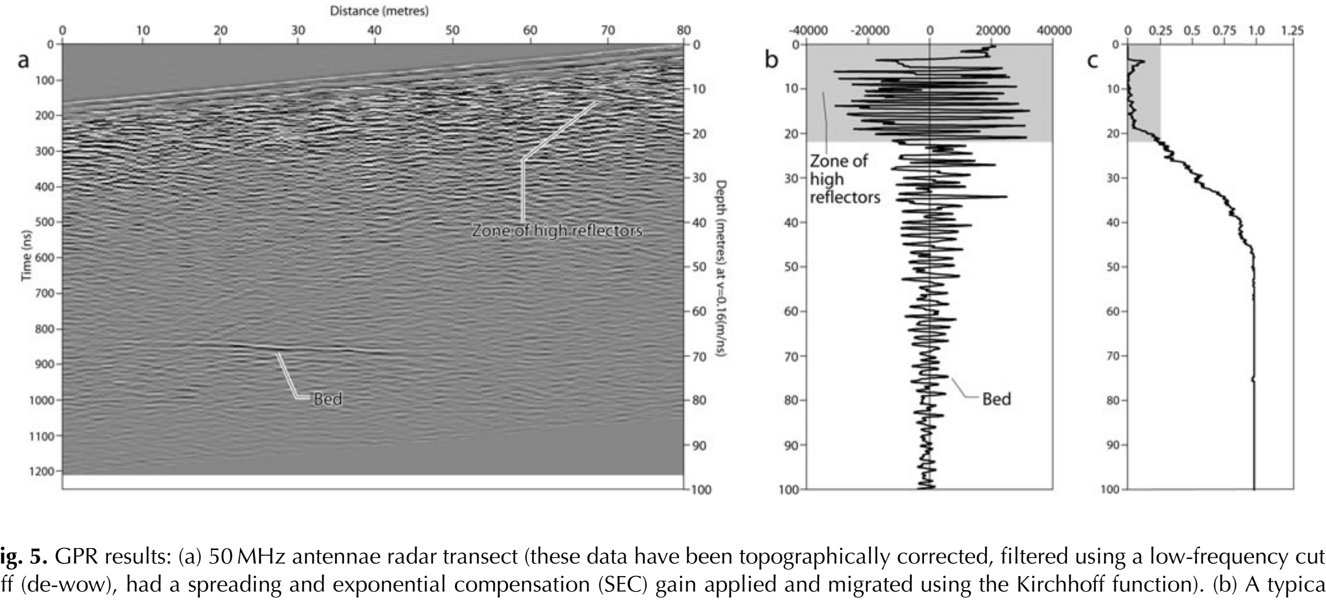

Fig. 5. GPR results: (a) 50 MHz antennae radar transect (these data have been topographically corrected, filtered using a low-frequency cut-off (de-wow), had a spreading and exponential compensation (SEC) gain applied and migrated using the Kirchhoff function). (b) A typical radar trace. (c) Average conditional values to demonstrate the location of the base high-amplitude reflections.

Table 4. Depth of surface high reflectors

Year	Transect	Depth of surface disturbance m
2003	A1	19.6
	A2	19.68
	A3	17.76
	AA	12.0
	AB	2.8
	AC	21.04
2004	B1	13.12
	B2	29.92
	B3	30.24
	B4	30.64
	B5	30.8
	B6	29.29
	B7	8.96
	BA	29.04
	BB	34.64
	BC	31.6
	BD	37.44

inspection and used to detect the boundary using the following method (Fig. 5b):

1. For each individual trace the amplitude was tested to see whether it was above a given threshold; taking A_x as the running 16 ns mean amplitude (as this was the mean length of a cycle) and T_1 as a threshold value of 10^8, $A_x^2 \geq T_1$ was evaluated (0 if true, 1 if false).

2. For each transect, the means of the conditional values were calculated, and the first time they passed a threshold value, this was taken as the depth of the surface radar disturbance if $X \leq T_2$ (where X is the conditional value mean over the transect, $T_2 = 0.25$).

Figure 5c shows X plotted against the radar signal strength to demonstrate how this method can automatically detect the base of the zone of high reflectors.

Table 4 shows that the results from 2003 range from 3 to 21 m with an average of 15 m and in 2004 the zone ranged from 9 to 37 m in depth with an average of 28 m, so the transceivers at 35 m were at sufficient depth to collect radio data from the bed.

Probe insertion

During summer 2004, three probes were inserted into the ice and five into the till (including one resting on a clast). The probe insertion technique depended on the nature of the borehole. After drilling, the boreholes either drained or remained water-filled. In those that remained water-filled, the probes were installed by gently dropping them into the holes and relying on gravity for them to sink to the base. In the boreholes that drained, the probes were lowered on fishing line, which was detached afterwards.

Towards the end of the hot-water drilling, till was 'blasted' away at the base by maintaining the jet at the bottom for a further 15 min. We then lowered the probes into this space, and assumed that the till would subsequently close in around them. Although we attempted to remove till from the base of the borehole with a special attachment to the subglacial sampler, this failed to convincingly remove any more till than the hot-water drilling technique.

In 2004 there were large clasts exposed at the base of some of the boreholes. In this situation, the probes rested on top of these large clasts, and this simulated the imbrication commonly seen in tills. In all cases, the borehole camera was used to check that the probes were placed correctly.

Probe data

The base station functioned from 10 to 15 August, 18 October to 8 November, 23 November–6 December and 18 February to 24 May, and 7 August onwards. A total of 859 days of probe data (36 078 sensor readings) were received. Table 5 shows the details of each probe: 66% of the englacial probes responded (total of 269 days, ranging from 1 to 268 days) and 100% of the subglacial probes communicated (total of 574 days, ranging from 1 to 377 days). There was no correlation between communication distance and survival rate (Table 1). Table 5 also shows how the sensors in the different probes functioned. Case stress failed to function in three of the probes, probably due to damage when sealing the probes.

Figure 6 shows how the success rate (calculated as the percentage of probe days received) declined over the year. Loss was greatest in the autumn, but stabilized during the winter. The reason for probe loss is not known. Probes 2 and 6 failed after the first day, and probes 3–5 failed whilst the base station was not working, so their 'death' was not monitored. Only probes 7 and 8 were monitored during their final days, but since there were no sudden changes in

Table 5. Probe data collected August 2004–August 2005

Probe	Days data sent	Working sensors					Date lost
		Water pressure	Tilt	Temperature	Case stress	Resistivity	
1	0	–	–	–	–	–	–
2	1	✓	✓	✓	✓	✓	7 August 2004
3	9	✓	✓	✓	✓	✓	15 August 2004
4	268	✓	✓	✓	✓	✓	24 May 2005
5	117	✓	✓	✓	✓	✓	6 December 2004
6	1	✓	✓	✓	✓	✓	7 August 2004
7	70	✓	✓	✓	×	✓	20 October 2004
8	377	✓	✓	✓	×	✓	24 August 2005

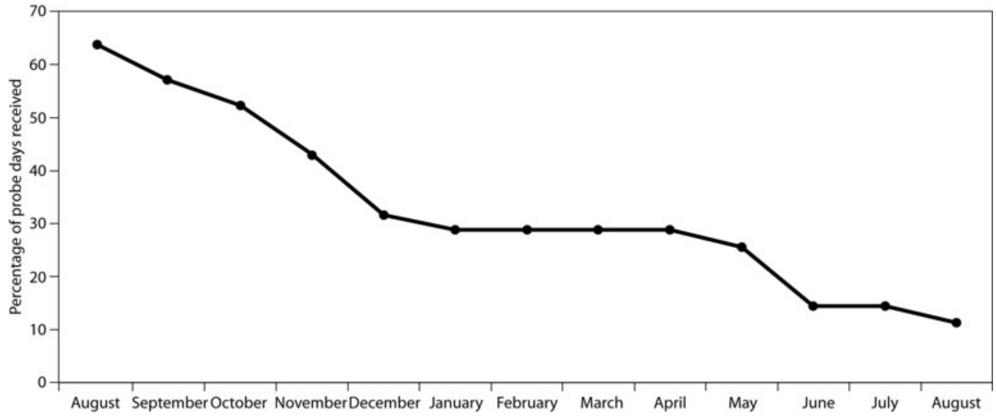

Fig. 6. Success rate (measured as a percentage of probe days per month from the initial eight probes that responded) from August 2004 to August 2005.

any of the readings (nor an increase in data errors), we assume they were removed by subglacial processes (e.g. glacial or fluvial erosion).

In Table 1 an initial communication distance is shown, which is the distance from the transceiver to the probe when it was deployed. However, as the upper part of the glacier moves faster than the base, the communication distance increases over time. Glacier surface velocity at the site was measured to be approximately 20 m a^{-1} between August 2004 and August 2005. It is assumed that the transceiver (which was positioned at 50% of the ice depth) moved 72% of the englacial ice movement (Harper and others, 1998) and that the till moved 25–85% of the surface ice movement (Boulton and others, 2001). This could increase the potential communication distance by approximately 1–4 m in 1 year. The maximum transmission distance for each probe that worked longer than 10 days was calculated, taking into consideration the geometry of the probes relative to the transceiver, the length of survival and the relative movement in ice and till described above. The results are shown in Table 1 and it could be seen that the maximum communication distance attained over the 2004/05 period was 36.26 m.

Results from probes in the ice and till

Figure 7 shows the resistivity and *x* tilt angle data from the two probes with the longest records. Although the *x* and *y* directions are relative, an estimate of their position can be determined by reference to the borehole video taken after deployment. Probe 4 was inserted into a borehole that did not reach the bed, so the results must reflect an ice probe. Probe 8 was deployed in a till-based borehole, and video images show it resting on the till surface. Table 6 summarizes the mean and standard deviation (SD) of the data from the englacial (probe 4) and subglacial (probe 8) probes over the same time period (August 2004–May 2005).

There are distinct differences between the englacial and the subglacial probes, in both their overall values and seasonal pattern. The resistivity of the ice probe (probe 4) was generally low, until March when it rose to a maximum level, at the same time as the *x* tilt angle became constant (after fluctuating for the previous 7 months) and the temperature remained at a constant low value (0.03°C, SD = 0.03). We suggest this reflects the ice probe becoming frozen into the ice in March after spending the winter in an englacial water-filled cavity (which explains the overall high temperatures, low water pressures and variable tilt angles).

In contrast, the resistivity of the subglacial probe (probe 8) was generally high, apart from oscillations in the autumn and a low-resistivity event in April. We suggest that in autumn the boreholes are still open to the atmosphere and the resistivity responds to precipitation events, the generally high resistivity during the winter reflects the probe's contact with dry and/or moist till, and the April event reflects water in the subglacial environment supplied from the 'spring event' (Iken and others, 1983). The temperature was constantly low (but higher than the ice probe once it was frozen in) and the tilt angles in the subglacial probe had low variability, but slowly increased throughout the year (January–August) reflecting increasing ice velocity. We suggest that the subglacial probe became incorporated into the till on the basis of resistivity, temperature and tilt angle readings although the depth of incorporation is not known.

CONCLUSIONS AND FUTURE RESEARCH

Designing a sensor network for glaciers was a challenging task because of the problems in predicting the behaviour of radio systems and power sources and because of difficulties in building electronic devices that are sufficiently strong and waterproofed to survive such a hostile environment.

The probes transmitted their data from 1–366 days over at least 36 m through ice and till, and provided data on temperature, water pressure, case stress, resistivity and tilt angle. Weather, GPS, other glaciological data and diagnostic data were also collected.

The next steps for the research are:

1. To increase reliability of the probes – future probes will be designed to operate at 173 MHz and have an improved sealing technique.

2. To design a probe location system.

3. To develop 'smarter' probes, which are networked together to allow inter-probe communication and modify their own data sampling strategies.

4. To design the system to be more 'user-friendly' for glaciologists to install and operate.

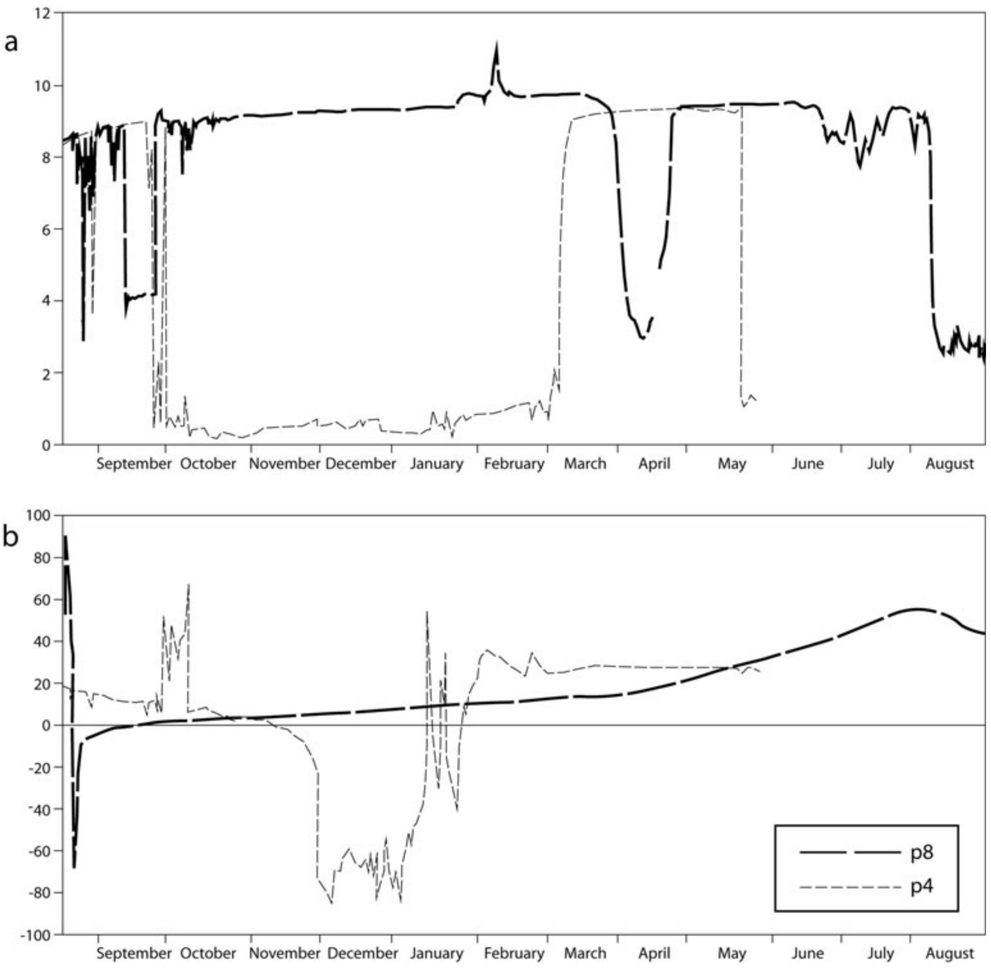

Fig. 7. Probe data from August 2004 to August 2005 from probes 4 (in the ice; short dashes) and 8 (in the till; long dashes): (a) resistivity; (b) *x* tilt angle.

The use of 'smart' devices to monitor the environment is a logical next step in Earth system science. The glacial environment is a particularly difficult one in which to make such a system function because of the logistical problems associated with ice, water, sediment and the hazards of a continually changing glacier surface (crevassing, etc.), all situated in a remote location. However, if such a system can be made to work in glaciers then the technology may be transferable to other remote and hostile locations. We have reported on the design and success of the GlacsWeb system which will be an important tool in the monitoring and understanding of subglacial processes and glacier dynamics.

Table 6. Summary of mean sensor values in the ice and till (August 2004–May 2005)

	Ice (probe 4)		Till (probe 8)	
	Mean	SD	Mean	SD
Temperature (°C)	0.8	0.80	0.15	0.03
Water pressure (m)	9.64	19.83	24.88	31.67
Resistivity (MΩ)	3.84	4.09	8.69	1.68
Tilt angle (*x*) (°)	4.33	33.95	9.63	11.72
Tilt angle (*y*) (°)	–39.3	29.82	–16.42	6.28

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