

# Glacsweb: a sensor network for hostile environments

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**Abstract**— A sensor network is described which obtains data from nodes on and inside glaciers. Power management through scheduling and selective control is used to allow a lifetime of at least one year on batteries. Radio links in the glacier and across 2.5km distances are used for data and commands. The prototype system was installed in Norway in 2003 and this paper describes details of the full design for 2004 through discussion of the lessons learnt.

**Index Terms**— sensor network, glaciology, radio communications, low power, environmental monitoring

## I. INTRODUCTION

Recent developments in wireless network technology and miniaturisation have meant that for the first time, the environment can be realistically monitored. These studies can potentially provide advances in environmental science, vital hazard warning as well as sensor network engineering. This is particularly important in remote or hazardous environments where many fundamental processes have never been studied due to inaccessibility.

The overall aim of this project is to produce a sensor network capable of measuring several parameters relating to ice caps and glaciers. This involves placing sensor nodes in extremely hostile environments: underneath, on and inside glaciers. The hazards are not confined to mechanical problems due to the weather and cold but also to radio communications. Together with the size and power constraints this has led to a variety of solutions to produce a working system.

There have been few sensor networks deployed in the environment. Of particular relevance here are NASA/JPL's project in Antarctica [1], NASA/JPL's Huntington Gardens project [2], Berkeley's habitat modelling at Great Duck Island [3] and the CORIE project which studies the Columbia river estuary [4].

One of the most important elements of climate change is its affect on sea level rise. Glaciers are a key

element in this behaviour, but their behaviour is poorly understood. Today 90% of the discharge of West Antarctica is not controlled by mass balance, but by subglacial behaviour [5]. Our research aims to use technological advances to understand the behaviour of rocks beneath the glacier in order to understand both the dynamics and estimate glacier motion [6].

At the same time, the overall aim of this research is the development of technology to understand and monitor glacier behaviour. The discharge from glaciers feeds directly into the sea, to either raise sea level (if glacier melts due to global warming). In the case of the Norwegian glaciers, they feed into the north Atlantic and so bring increased supplies of fresh water into the sea which may cause the shut down of the thermohaline circulation which would cause a dramatic decrease in North West European temperatures [7]. Both sea level rise and climate change directly affect society so any monitoring and understanding of this process will help provide solutions to these far reaching effects.

The glaciological objectives are to measure the relative motion of the bed to the surface, study the motion of small rocks in the bed and other parameters useful for subglacial dynamics. These are the most novel and challenging problems, which are combined with more conventional data from weather stations and satellite imagery. In order to mimic rocks, sensor nodes (probes) are placed in and under the glacier which contain appropriate sensors but must communicate their data to the surface via radio communications.

These requirements led to the following technical objectives:

- miniaturisation
- low power design
- ad-hoc networking
- autonomous and adaptive behaviour
- position sensing of the probes

We were particularly interested in how the hostile environment would influence the design of the network and hardware. We also expected differences between theoretical designs and the final designs moulded by experience.

Work on the prototype system began in November

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2002 and it was deployed in Briksdalsbreen, Norway in the summer of 2003. This glacier was chosen because it had the appropriate logistics and glaciological conditions. The glacier is fast-moving and an outlet of the largest ice-cap in mainland Europe. It has advanced 400m since 1988 and is resting on unconsolidated sediment. Due to tourism the glacier is easily accessible, has GSM telephone coverage and mains electricity and ISDN access in a nearby (2.5km) camp site.

This paper briefly describes the data from the prototype, describes the second system deployed in the summer of 2004 and discusses the new developments based on experiences with the prototype.

## II. SYSTEM ARCHITECTURE

Figure 1 shows the overall system which comprises four main elements: probes in/under the glacier, a base station on the ice and a reference station which relays data to a sensor network server (SNS) in the UK.

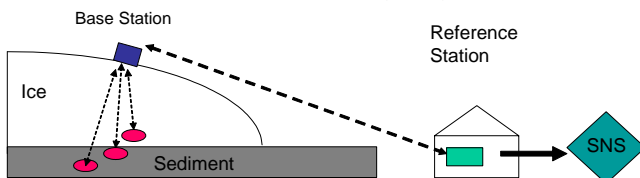


Fig. 1. System overview

To save power and simplify the communications protocols a communication window is used during which all the systems and communication links are open. The probes are passive and only respond to commands from the base station such as “data-read” or “set-time”. This avoids the use of potentially power-wasting collisions which would occur if probes tried to transmit autonomously. The design assumes that radio communications will be intermittent so every system which fetches or gathers data maintains a data store locally. The risk with a communication window is that if there are clock drifts subsystems will become “lost” but this has been minimised by broadcasting GPS time regularly.

The Reference Station is the gateway for transferring data and manually controlling the entire system from Southampton. It also acts as a reference point for the differential GPS system for measuring supra-glacial displacement. Radio communications use the license-exempted 433MHz and 468MHz channels.

The Linux-based sensor network server contains the final data repository and provides web access for researchers. It also provides the backup text message server capable of receiving data directly from the base station.

### A. Probes

The electronics and sensors are enclosed in a plastic egg-shaped capsule. Each capsule is composed of two halves which are permanently bonded (See Fig. 2). Each probe is equipped with the following sensors: pressure, temperature, orientation (tilt in three dimensions), external conductivity and strain gauge. The probes are inserted using a hole cut with a hot water drill and are not recoverable. The external diameter was fixed by the hole size produced and is now 68mm wide.

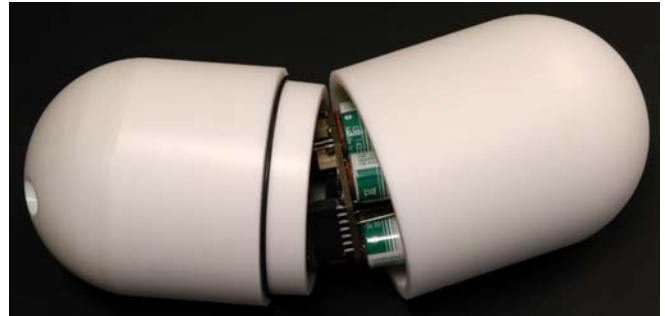


Figure 2. Probe housing shown open.

The orientation is measured using two dual-axis 180 degrees micro-electromechanical (MEMS) sensors. A PIC microcontroller (PIC16F876) reads analogue sensors with the built-in A/D while other sensors and power control is accessed via the (I<sup>2</sup>C) bus. This is also used to communicate with the real-time clock (RTC) and a 64k bytes FlashROM. 3.6V Lithium Thionyl Chloride batteries were chosen due to their high energy density and low temperature characteristics. The prototype used dielectric antennas measuring only 5x7x0.5mm which were omnidirectional. However these have been replaced by conventional helical antennas which have better efficiency but are much larger. Figure 3 shows the probe’s architecture.

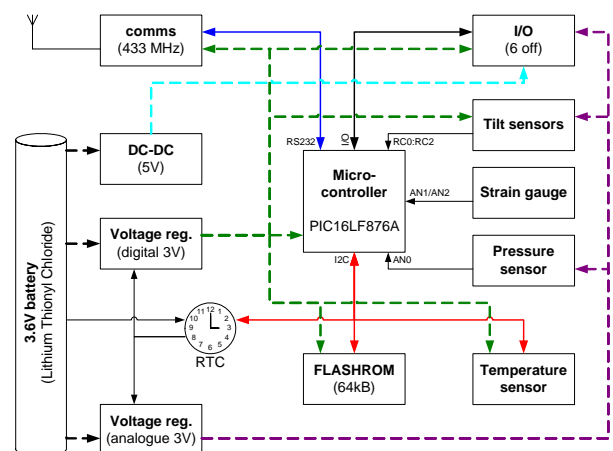


Fig. 3. Block diagram of Probe (version 2)

Probes collect data six times daily in order to save power and the transceiver is only enabled once each

day. This acquisition rate is acceptable as the data is not expected to change rapidly. In sleep mode all the electronics except the RTC are powered off and the current system consumes only 10 $\mu$ A in this state. Powered on they consume only 4.2mA (with transceiver off). In order to fit the electronics into the small package a stack of three octagonal PCBs are used (digital, analogue and radio) which also makes the system modular. Battery voltage is measured and stored along with other sensors as it is essential system status data.

The data collected (100 bytes/day) is stored in FlashROM in a ring buffer to allow for communication breakdowns.

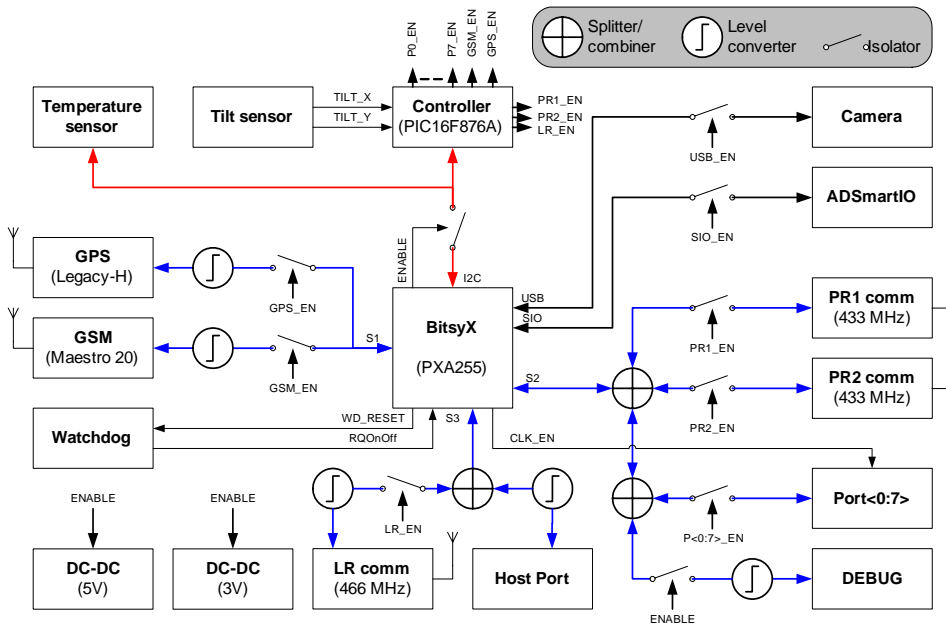


Figure 4 Base Station Architecture and installation on glacier

### B. Base Station

The Base Station controls the probes, gathers surface data and links to the reference station in the valley. Local data is fetched from a weather station, webcam and ultrasonic snow meter. 60AH of large lead-acid gell batteries are used together with a 10W solar panel for power. A permanent weather and movement tolerant pyramid structure holds sensors, antennas and tethers the equipment (Fig. 4). A differential GPS unit is read daily to measure its location in conjunction with data from the reference station's GPS. A 500mW radio modem provides a 9600 baud link 2.5km down the valley to the reference station PC.

The prototype base station was controlled by a PIC16F877 MCU (main controller) with ancillary PICs used to control the GPS and GSM controllers. The FlashROM, RTC, temperature and tilt sensors were identical to the Probe's. Although power-efficient this was not easily reprogrammable so the current system uses a StrongARM-based board (BitsyX) running Linux. This will allow better remote

access as diagnostics and maintenance has been found to be a major challenge. Figure 4 shows the main detail including the extensive power control over each device. Six peripheral devices use RS232 ports but the main board only has three, so a custom switcher has been integrated into a new board which also has the power-control devices. Each unit can be completely powered-off when not in use. A web-cam allows the general condition of the site to be observed and uses the USB port.

A GSM modem was implemented in the prototype which allowed data to be sent directly to the UK server via text messages (SMS) if the long-range link was down. This was highly successful and the final system



will include dial-in capability for emergency access as well.

The I<sup>2</sup>C bus is used to send commands to the PIC which controls the power and also has tilt and temperature sensors. Tilt was found to be useful in determining if the box was about to slip into an approaching crevasse for example.

The GPS system is used in conjunction with the GPS unit in the Reference Station to reduce the spatial errors caused by the surface movement (aprox 30m/year).

### C. Reference Station

The Reference Station is a mains-powered 500MHz EPIA-PC running Linux and located in a café in the valley. This low-power PC format was chosen as can be supported for longer on a UPS as well as being small and near-silent. It is 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 one hour GPS file daily. Each day it sends all new data to the data server in Southampton

via ISDN dial-up and archives all data on disk as a backup.

### III. COMMUNICATIONS

The short-range communication has to penetrate up to 100m of glacier ice and some sediment. Under these conditions, RF signals degrade significantly. The centre frequency is a compromise between antenna size and RF losses. Omni-directional dielectric antennas avoid problems with varying probe orientations and are extremely small. The prototype used Adlink 868MHz transceivers with good sensitivity and efficiency. After a transmission test the true losses in glacier ice were found to be much higher than expected and the base station's transceiver was lowered down a 30m hole to reduce the distances involved. The new version uses 433MHz, which is still high for wet ice but our transceiver PCB includes a 100mW power amp to boost the signal. The base station will have two wired transceivers 30m down holes to avoid wet ice, allow for redundancy and self-tests. We are also dispensing with the dielectric antennas in favour of conventional compressed helical in order to gain power.

The distance between the Base and Reference Stations is 2.5km without line-of-sight. For reliable communications 468MHz high-powered (500mW) radio modems were employed which integrate some error correction.

A 9600 baud rate is used in all radio communications, which is sufficient for the amount of data handled and leads to transmission times of under 10 minutes down valley.

#### A. Communication Protocol

A robust communication method is essential to prevent noise from interfering with system operations and to maintain data integrity. To achieve this, a packet-based communication protocol with error detection was devised for probe communications. The PIC processors do not have the capacity to cope with TCP/ip and in the prototype the base station also used these packets for reference station communications. This has been replaced by TCP/ip over PPP dial-up.

The probe packet structure is shown in Fig. 5. The first byte contains the header and the size of the data field. The second byte is the ID of the destination and the command (CMD) field allows up to 256 different commands to be defined. The data field is 1-16 bytes and the checksum (CS) is used to check packet integrity.

0	1	2	3 ... 18	19
HD/SZ	ID	CMD	DATA	CS

Fig. 5. Communication packet format

In the current set up, three types of packets are recognized: command, reply and broadcast packets. Command packets are sent by the Main controller (or from Southampton) to any other device. The device in question responds with a reply packet. If a valid reply packet is not received within a preset duration, this signifies communication (e.g. checksum error) or topology (e.g. unknown device) error. Only broadcast packets do not case a reply and these are used to send information to all devices simultaneously (e.g. setting clocks).

TABLE I. COMMUNICATION SEQUENCE

Time	Probe	Base Station	Ref. Station
0000	Data log		
0300		GPS log	GPS log
0400	Data log		
0800	Data log		
1200	Data log		
1600	Comms	Comms	Comms
1900			Transfer
2000	Data log		

#### B. Sequence of Events

The daily sequence of events for recording and transferring data is shown in Table I. At the end of each period, the Probe and Base Station configures their RTCs to the next "wake-up" time before shutting down.

Probes only record their sensors during *Data log* periods. During the *Comms* period, they enable their transceivers for a fixed duration after recording their sensors. The Base Station powers up during this period and reads its own sensors, broadcasts the GPS system time and requests unseen sensor readings from the Probes. In addition, the Reference Station connects to the internet to allow communication between Southampton and the entire system. This *communication window* opens for a short duration once the systems are idle.

The Base Station and Reference Station also "wake up" during the *GPS log* period to read GPS data. A separate GPS period allows its timing to be shifted manually according to the time of year because satellite visibility varies considerably. The day's data are transferred to the server in Southampton during the *Transfer* period.

#### C. Ad-hoc networking

Due to the wide variation in radio losses in the glacier it is possible for probes to loose contact with the base station. Hence it would be useful to include a probe to probe ad-hoc network which would allow data to pass across them to the base. This would also be expected to save energy if less power was acceptable for inter-probe communications. Of course the power drain on

an overused intermediate probe has to be minimised as well. With this in mind an algorithm has been developed which requires a minimum of setup because the probes should be on for a short time only and can not afford to negotiate too much.

#### IV. LOCATION SENSING

One of the requirements is to locate the probes to accuracy better than 1m. A time-of-flight system has been designed which measures the distance to five antennas on the surface. A command to a probe tells it to send back a pulse and this stops a 1GHz counter on each surface receiver. Data from the five counters together with their position (measured with dGPS) and the velocity of the RF in ice (16cm/ns) provides the position of the probe. This technique will be tested in the summer of 2004.

#### V. PROTOTYPE RESULTS

The entire system was installed at Briksdalsbreen, Norway, in August 2003. Nine probes were deployed, mainly at the ice-tilt boundary (50m to 80m deep). Perfect results were not expected immediately due to the water in the holes; which were expected to close up. However the preliminary results were useful and provided a way of testing the system. Short monitoring fieldwork was carried out in Autumn and Spring to upgrade the Base Station and check the system's condition. Some holes had closed while others were still draining surface water, so these would have caused communication problems.

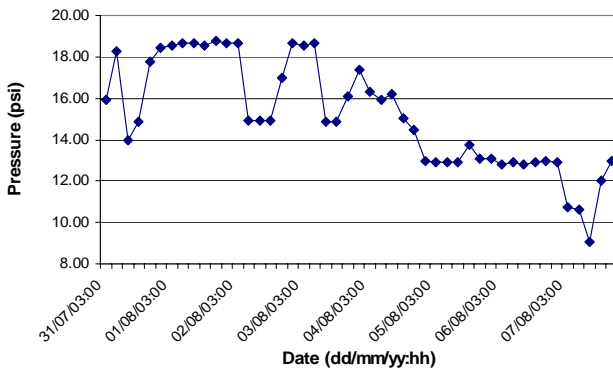


Fig. 5. Probe 8 Pressure Readings

##### A. Prototype Probe Data

Temperature and pressure readings were only received from one Probe. The temperature was a constant 0°C as expected. The tilt readings were also constant. Probe 8 was wedged approximately 20m down a borehole and lost communications after the 7<sup>th</sup> of August. This is probably due to it slipping into the water-filled zone at the bottom of the hole. The drop in pressure seen in Fig. 5 (error is approximately  $\pm 3$ psi) is still unexplained.

##### B. Base Station Data

The Base Station has two sets of data so far: one each before and after replacement of the main board. The data shows its battery voltage (Fig. 6) tilt and temperature (Fig. 7).

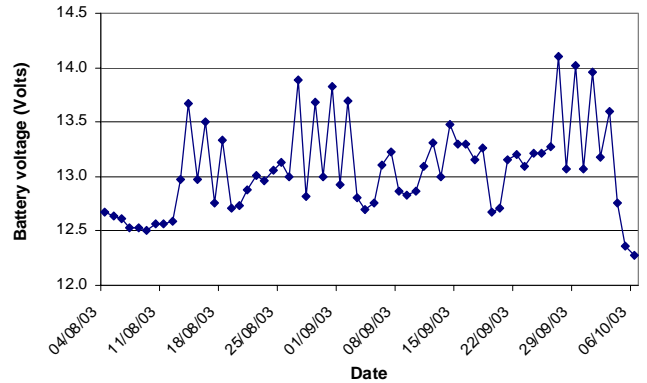


Fig. 6. Base Station battery Voltage

The battery level fluctuated between 12.3V and 14.2V over the course of 65 days (and was still 12.2V in April 2004). This ripple is due to the solar panels charging the batteries on bright days and it can be seen that overall battery charge remains high during the summer.

Figure 7 shows the relationship between the base station's tilt and temperature. The tilt indicates that the Base Station moves slightly during warm periods (eg Nov 11 2003). The temperature on the glacier slowly decreased during winter and after Feb 11 2004 snow fall stabilised the readings.

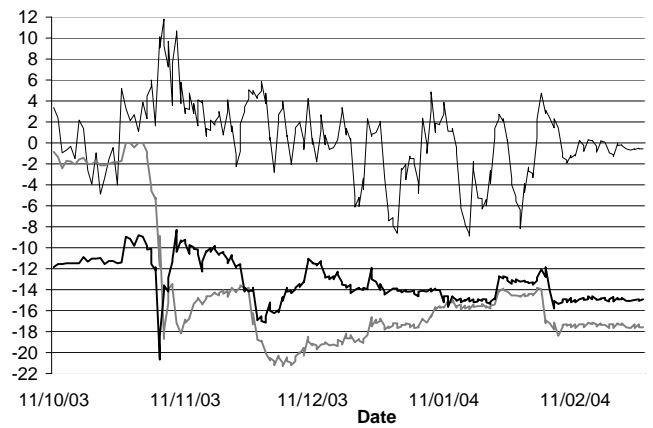


Fig. 7. Base Station temperature/C (upper trace) and box tilt (lower two traces/degrees)

#### VI. CONCLUSION

This research has necessitated an interdisciplinary team including people from the following fields: glaciology, electronics, computer science, communications, mechanical engineering and surveying. Our experience shows that a prototype installation in the field is necessary in order to actually solve all the engineering problems. It has also highlighted the importance of remote diagnostics and

control. The lessons learnt will ensure that the 2004 system will be a stable platform for sensor network research including ad-hoc networking and autonomous adaptive behaviour.

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