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High-Resolution Sensor Network for Monitoring Glacier Dynamics

I. Martin, T. O'Farrell, R. Aspey, S. Edwards, T. James, P. Loskot, T. Murray, I. Rutt, N. Selmes, T. Baugé

***Abstract*—This paper provides an overview of a wide area wireless sensor network that was deployed on the calving front of the Helheim Glacier in Greenland during the summer of 2013. The purpose of the network was to measure the flow rate of the glacier using accurate satellite positioning data. The challenge in this extreme environment was to collect data in real time at the calving edge of the glacier. This was achieved using a solar powered 2.4 GHz Zigbee wireless sensor network operated in a novel hybrid cellular/mesh access architecture consisting of ice nodes communicating with base stations placed on the rock adjacent to the glacier. This highly challenging transmission environment created substantial signal outage conditions which were successfully mitigated by a radio network diversity scheme. The network development and measurement campaign were highly successful yielding significant results on glacial dynamics associated with climate change.**

***Index Terms*—PHEN, SYST, NET, WSN, GPS, extreme environment, glacial calving, Helheim, Greenland.**

I. INTRODUCTION

THE mass balance of the major ice sheets, and therefore their contribution to global sea-level rise, is controlled primarily by the speed of fast-flowing ice streams and outlet glaciers, terminating in ocean waters. During the early 2000s, there was a doubling of ice discharge in Greenland, which primarily resulted due to an increased flow rate of these tidewater glaciers [1] and it is possible that this phenomenon has been triggered by changes in the ocean waters at their calving margins [2]. Therefore, there is significant scientific interest in characterising the relationship between the changes in flow (i.e., the dynamics) of a tidewater glacier and the changes in the terminus position and calving rates of the glacier.

Insights into the dynamics of a tidewater glacier, in particular understanding the primary mechanisms for calving, enable the relevant dynamic processes to be modelled in a computer simulation of the ice sheet and its outlet glaciers in order to enhance the prediction of how such tidewater glaciers respond to climate change. To enhance our understanding of the calving mechanisms, detailed observations of iceberg calving events are required. However, these are difficult to obtain because of the challenges faced when placing and maintaining instrumentation on the heavily crevassed ice surface. Currently, the majority of knowledge on glacier flow dynamics is derived from remote sensing.

To obtain the right observations, a network of expendable Global Positioning System (GPS) sensors was deployed at the calving edge of the Helheim Glacier in Greenland. The GPS capability was used to make near real time velocity and uplift measurements accurate to a few centimetres. The GPS sensors were connected to each other as well as to base stations via a self healing network of expendable, low-power wireless transceivers. The innovative nature of the network and its components made it economically and logistically possible to deploy a relatively large number of sensors by helicopter on the calving region of the glacier. The velocity and elevation data from the GPS sensors was combined with remotely sensed velocity fields from satellite, airborne lidar and ground-based photogrammetry measurements in order to generate a synthesised dataset of high temporal and spatial resolution. This has formed a unique dataset for testing calving models and to improve the understanding of the controls on the contribution of these tidewater glaciers to sea-level rise.

The research reported in this paper has focussed on the deployment of a wireless sensor network in an extreme environment close to the calving front of the Helheim Glacier which is Greenland's third-largest outlet glacier. The glacier surface consists of crevasses and parallel fissures approximately 30 m deep and mounds of ice approximately 10 m above the local surface height of the glacier. Figure 1 illustrates the Helheim Glacier draining from the Greenland ice-sheet with the calving front and ice mélange (i.e. calved blocks of glacial ice), in the foreground. Figure 2 depicts the associated catchment area. The combination of harsh environment and glacial movement present significant challenges for the near real time measurement of flow speed and direction at the calving front of the glacier.

The project combined expertise in glaciology, GPS technology and processing, and wireless networks to design, install and operate a wireless network of GPS sensors at the margin of the heavily crevassed Helheim Glacier in South East (SE) Greenland. Moving at speeds of the order of 20 to 25 m/d, calving large icebergs along its 6 km calving front, the glacier is a major outlet of the SE Greenland ice sheet making it a challenging environment to monitor [3]. From lessons learned through the deployment of a small-scale field trial network in July 2012, a scaled up network consisting of 20 GPS

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nodes was deployed on the glacier during the summer of 2013. The on glacier ice nodes provide full code and phase dual frequency GPS data every few seconds to base stations positioned on rock at the edge of the glacier. Of the 20 ice nodes deployed, 19 communicated successfully with the network base stations. High resolution position data available from the high temporal sampling has allowed calving events to be monitored to the point of sensor loss, differentiating the real time capability of the network from previous solutions.

Fig. 1: Calving front of Helheim Glacier.

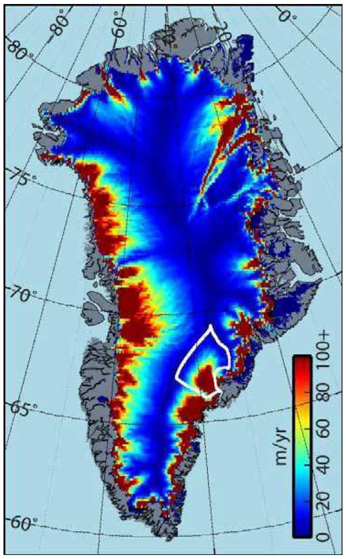

Fig. 2: Helheim catchment location in Greenland (white boundary shows catchment area). Background image is balance velocity - Created at the University of Montana by Jesse Johnson in July 2009.

II. LITERATURE REVIEW

Such a remote and hostile terrain makes direct access both difficult and expensive when installing observation platforms, consequently glacier observation is frequently conducted using satellite imagery. This, however, typically limits the information on flow rates to a repeat cycle of 10 days. Given that the flow rate of the ice streams greatly exceed this resolution, surface flow measurements using GPS data are attractive. Dual frequency GPS equipment can provide positional data every second with an accuracy of 1-2 cm in plan and 2-5 cm in vertical whereas single frequency GPS equipment can exhibit positional accuracy of several tens of metres. Reference [4] provides a review of remote sensing techniques employed in glaciology studies. In particular, the value of GPS in determining glacier surface velocity is discussed.

Previous significant research on monitoring the surface velocity of a tidewater glacier in Greenland using GPS sensor nodes is reported in [2], [5]. The research team successfully operated a network of continuously recording GPS receivers on the Helheim Glacier for periods of 54 and 55 days during the summers of 2007 and 2008, respectively. In the field trial of 2007, a total of twelve GPS receivers were deployed on the glacier. The majority of nodes were deployed along the glacier's central flow line spanning a total distance of 20 km. A small number of nodes were deployed offset from the centreline while a few nodes were positioned immediately behind the calving front. In the 2008 field trial, 22 nodes were deployed again focussing on the major flow lines of the glacier but not extending to the calving front. In both field seasons some GPS receivers were positioned on rock sites next to the glacier in order to provide stable local GPS reference frames. Results on glacier velocity were obtained using a 15 s sampling interval.

In contrast, the research reported in this paper focusses on the deployment of a wide-area wireless sensor network of 20 GPS nodes immediately behind the calving front of the Helheim Glacier. Using a sampling interval of ~ 7 s, the network provided near real time positioning information which can be translated into high resolution spatial and temporal information about the dynamic behaviour of the glacier at the calving front. The wireless network used commercial off the shelf (COTS) 2.4 GHz Zigbee technology and purpose built antennas to achieve reliable communication over such a hostile environment. The network was deployed for 50 days during the summer of 2013.

III. NETWORK EQUIPMENT

The network consisted of 20 on-ice GPS receiver nodes and 4 logging base stations placed on the rock at the side of the glacier. Zigbee transceivers operating in the 2.4 GHz ISM band were used to transmit the GPS data from the ice nodes to the loggers. Zigbee transceivers were designed for the hostile radio frequency (RF) environments and provided a low-power, low-cost wireless network with automatic retries and automatic network formation [6]. The whole network was powered by solar panels with backup batteries to span cloudy days and night time. Base stations acting as Zigbee network coordinators collected data from the ice nodes. Figure 3 illustrates a logging base station whereas Figure 4 illustrates an ice node.

To achieve high temporal sampling rates, ~ 7 s for each ice node, the network was divided into 4 sub-networks of 5 nodes each operating simultaneously. Typically, Zigbee uses carrier sense multiple access with collision avoidance (CSMA/CA) in order to reduce the number of transmission collisions.

However, on the glacier this functionality is severely restricted because the crevassed surface shields the ice nodes from each other giving rise to the hidden terminal problem. Therefore, RF collisions within a subnetwork were avoided by employing a base station round robin (RR) scheme that polled each ice node for a message to which it replied with GPS data.

The RR scheme was designed and implemented as firmware at the router level of each node participating in the network. Each base station housed a router per Zigbee unit responsible for coordinating and polling the ice nodes within its association list. Also, each ice node housed a router per Zigbee unit allowing an ice node to send GPS data when polled. The base station router sequentially polled each ice node in its association list with a fixed duty cycle of approximately 7 s. The RR protocol operated independently on top of the normal mesh and medium access control (MAC) protocols defined in the Zigbee standard. Each ice node was configured to allow at least two hops on the return path between the node and its base station. Thus, on occasions when data could not be returned to the base station in a single hop, the possibility existed for a node to send its data to the base station via at least one other ice node. In practice, the vast majority of data was returned in a single hop to the base station. At the data link level, access to the RF transmission medium was controlled by the CSMA/CA protocol. This protocol was operated in order to avoid the collision of radio packets caused by retransmission events at the boundaries of polling epochs. The number of retransmission attempts was set to 8 which is a default value for Zigbee.

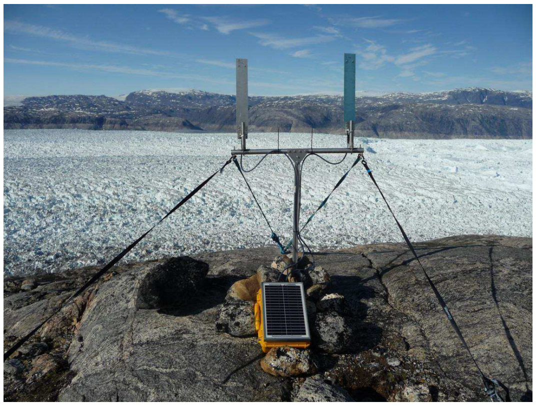

Fig. 3: Logging base station.

IV. RADIO DIVERSITY

To provide wireless diversity each ice node contains two completely independent Zigbee transceivers linked through an RF 3dB splitter to an omnidirectional antenna with a 3dBi gain. A schematic of the ice node hardware is shown in Figure 5. The two transceivers communicate with different base stations providing two distinct radio routes off the ice. For the 20 node network this leads to 8 subnetworks, each containing 5 ice nodes, operating in a different frequency band.

Figure 6 shows the nominal network layout and allocation of the Zigbee channels to the 8 subnetworks. The hexagons represent ice nodes coloured according to the frequency allocation chart whereas base stations are denoted by coloured squares. The green dashed lines show the beam width (at least 90°) of the 12dBi high gain base station antennas [7]. The channel allocation is chosen to maximise the frequency separation between collocated transceivers at both the nodes and the base stations to reduce adjacent channel interference. The network is split into North and South segments due to the very large scale of the glacier topography. With a maximum Zigbee transmit power of just 50 mW, 12 dBi antenna gain at the base station and 3 dBi antenna gain at the ice node, the network was designed to give radio coverage across the full 6 km width of the glacier [8].

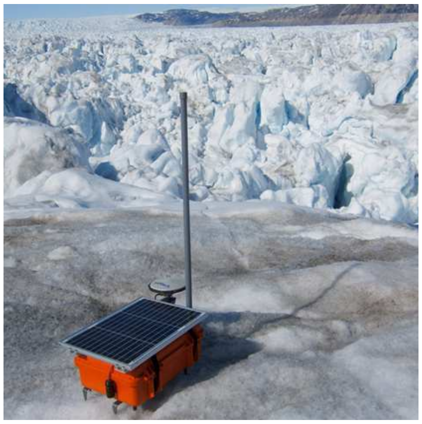

Fig. 4: Ice node.

The network configuration delivers diversity by transporting control and payload data to and from an ice node through two independent radio paths. Each radio path is supported by its own Zigbee unit. That is, every base station and ice node house two Zigbee units whereby each base station Zigbee unit coordinates its own subnetwork as depicted in Figure 6. In this respect, the RR, mesh and MAC protocols between Zigbee units within the same subnetwork node do not interact but instead provide independent data transport routes benefitting from spatial separation of the base stations. The GPS data returned from an ice node is logged separately at each supporting base station. Post field trial processing combined the two sets

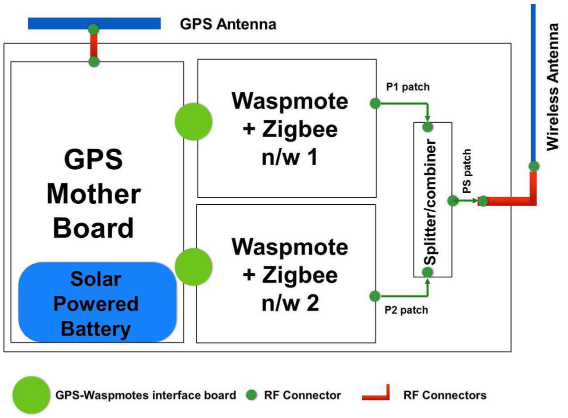

Fig. 5: Ice node subsystem diagram.

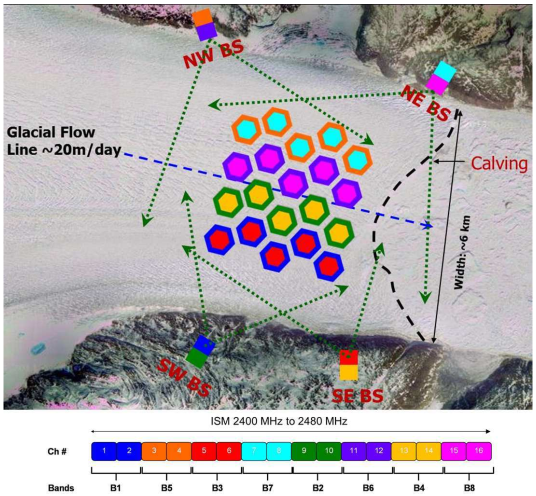

Fig. 6: Wireless network layout and frequency allocation.

of logged GPS data from an ice node into a single record. Since the subnetworks operated asynchronously, when both data sets were available the diversity process generated GPS positions more frequently that the planned 7 s duty cycle per ice node. More importantly, when one radio path was blocked, the other provided the required GPS data reliably.

Figure 7 shows successful GPS data reception at the base stations for each ice node. Vertical grey shaded bars show time periods of extensive calving activity. Visible data gaps at one base station but spanned by the other, demonstrate return channel diversity. Figure 8 shows the received signal strength from ice node 3 at the North East (NE) and North West (NW) base stations. Care taken on node deployment ensured that the initial received signal strength indicator (RSSI) was substantially above the hardware RSSI limit of -102 dBm.

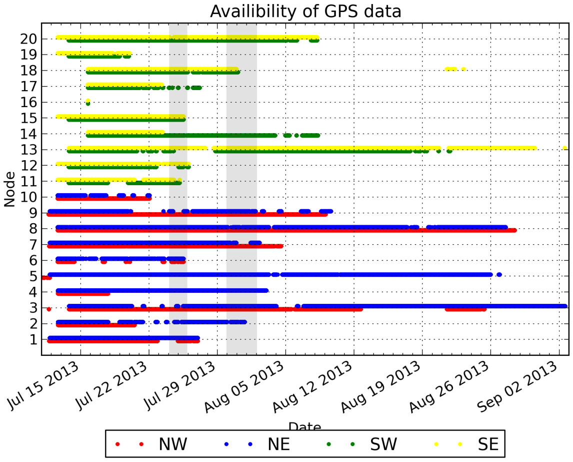

Fig. 7: GPS data profile over trial period.

Despite the node to base station range changing slowly, there are large changes in received signal strength at times dropping below the operational threshold of -102 dBm. This is due to the obstructions and multipath interference caused by the complex local radio environment - see Figure 4. The average RSSI agrees within ±3 dB of values obtained by modelling the environment [7]. Combining the data collected at the two base stations for this particular node covers the complete deployment period from mid July to the end of August 2013.

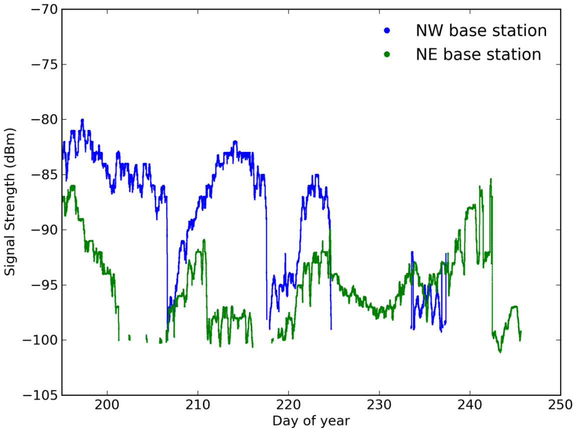

Fig. 8: RSSI at ice node 3.

V. GPS RESULTS

Over 7 million epochs of raw GPS observation data were recorded during the 2013 field season. The observation intervals for each ice node was in the range 4 to 8 seconds. Ice node positions have been estimated using Track (GAMIT v10.5) carrier phase relative positioning software. The GPS reference site was the NW base station. Processing was performed using the ionosophere free linear combination and CODE final orbits/clocks. Tropospheric zenith delay was modelled [9] and mapped to satellite elevation using the GMF [10], [11]. The Zenith wet tropospheric correction was not estimated due to the positional degradation it causes during periods of low satellite visibility. The ice node position was estimated at each epoch using a Kalman filter process noise of 1 cm/s to ensure capture of calving dynamics. Formal errors are between 1-2 cm in plan and 2-5 cm in vertical. This allows detection and isolation of tidal signals in the position time series which is useful to future data analysis.

Figure 9 demonstrates the high resolving power of the network right up to the time of the loss of a node. In Figure 9, the grey shaded vertical bars correspond to time periods of calving activity with node 11 being lost during a calving event at approximately 206.14 decimal days. These data provide valuable information about the glacier at the time of calving not previously measured [2]. The data will allow the authors to investigate fundamental questions such as: the detailed mechanics and dynamics of glacial calving; the significance of surface water in calving; and the relationship between the tides and calving events [12], [13].

VI. CONCLUSION

A robust wireless network of GPS sensors has been designed and successfully operated at the active calving front

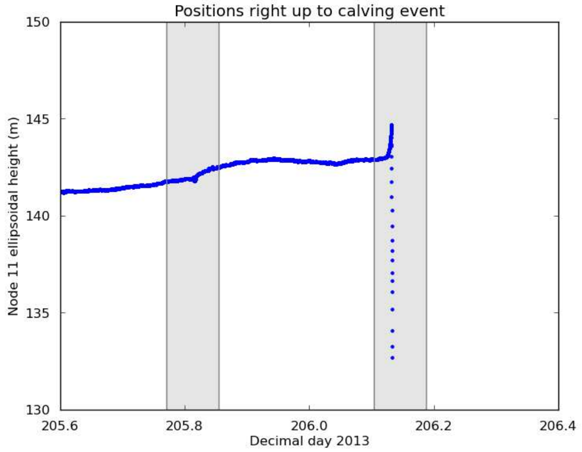

Fig. 9: Node 11 height profile showing node loss at the calving front.

of the marine outlet, Helheim Glacier. A key performance metric for the network was the signal outage rate defined as the percentage of time that the RSSI fell below the minimum received power level of -102 dBm. Analysis of the results demonstrated an outage rate of $< 1\%$ taking into account the gains achieved from radio diversity. The results demonstrate the significant benefit of using radio diversity to mitigate signal fading due to shadowing from ice pinnacles. Further, the network remained operational for the whole deployment period of 50 days, with network nodes being powered by lead acid batteries trickle charged from solar panels. No power outages were observed throughout the deployment period which can be attributed to the extended duration of sunlight available at high latitude during the summertime as well as favourable weather conditions. This enabled network tracking up to the point of node loss. GPS data processing provided formal errors between 1 to 2 cm (plan) and 2 to 5 cm (vertical), allowing detailed evaluation of the glacier dynamics at the calving front. GPS data obtained is one component of a unique and rich data set including >6000 oblique stereo-photographs and 1.2 TB of airborne data.

Importantly, the project demonstrated a number of key design lessons relating to the use of low cost COTS wireless network technology at the margin of a major tidewater glacier. Foremostly, it proved possible to use 2.4 GHz Zigbee radios to provide reliable radio communication over ranges >3 km when radiating just 50 mW of RF power. This was mainly achieved by the high placement of base stations giving a clear view across the glacier as well as using high gain antennas. Secondly, radio diversity exploiting the large separation between participating base stations provided a highly effective means of combatting shadow fading due to ice pinnacles as nodes moved relative to their associated base stations. Thirdly, it was possible to operate the network in a constant power-on mode without resorting to sleep-mode techniques to conserve energy. This allowed the network to operate in real time with a self-healing capability as nodes close to the calving edge were lost whilst maintaining successful GPS data retrieval. This network feature was achieved by developing each node as a low power Zigbee router powered off batteries charged by solar panels. The wireless network design proved to be highly robust in such an extreme environment and future applications such as volcano and landslide monitoring are currently being considered.

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