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Instruments and Methods

A wireless subglacial probe for deep ice applications

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ABSTRACT. We present the design and first results from two experiments using a wireless subglacial sensor system (WiSe) that is able to transmit data through 2500 m thick ice. Energy consumption of the probes is minimized, enabling the transmission of data for at least 10 years. In July 2010 the first prototype of the system was used to measure subglacial pressure at the base and a temperature profile consisting of 23 probes in two 600 m deep holes at Russell Glacier, a land-terminating part of the West Greenland ice sheet near Kangerlussuaq. The time series of subglacial pressure show very good agreement between data from the WiSe system and the wired reference system. The wireless-measured temperature data were validated by comparison with the theoretical decrease of melting point with water pressure inside the water-filled hole directly after installation. To test the depth range of the WiSe system a second experiment using three different probe types and two different surface antennas was performed inside the 2537 m deep hole at NEEM. It is demonstrated that, with the proper combination of transmission power and surface antenna type, the WiSe system transmits data through 2500 m thick ice.

INTRODUCTION

As reported in a comprehensive review by Clarke (2005), subglacial processes are important because they determine in part the large-scale behavior of glaciers and ice sheets. In ice-sheet modeling, the connection between melt processes and macroscale mechanics remains a serious knowledge gap. The most significant processes probably operate in a layer extending a few meters above and below the contact surface between glacier ice and the substrate of bedrock and sediment. They can have an influence on flow dynamics similar to or greater than those within the ice. The development of subglacial sensors that operate near the ice/bed interface improves our understanding of these processes. Wired borehole instrumentation has been developed over the past 30 years to monitor the subglacial water system, the underlying sediment or the glacier ice itself. Recent examples are studies on sediment deformation (Boulton and others, 2001), subglacial water pressure (Stone and Clarke, 1996; Engelhardt and Kamb, 1997) and temperature profiles (Lüthi and others, 2002). A problem with measurements of this type is that an electrical connection via a cable must be maintained for power supply and data transfer. Consequently, probes inserted in sediments cannot move freely (Hart and others, 2006) and the electrical connections can break as a result of cable stretching due to ice deformation and basal motion (Lüthi and others, 2002). Alternatively, the GLACSWEB project (Martinez and others, 2004; Hart and others, 2006) and Harrison and others (2004) successfully demonstrated the use of wireless systems in a subglacial environment. Further advantages of a wireless probe system (especially for temperature profile measurements) include the simple attachment of probes to a rope in the field, thereby gaining flexibility, making preparations unnecessary and allowing all probes to be packed safely in a single box. Compared with conventional cabled systems, the size and weight of a wireless system can be less when using a Kevlar rope and a small winch system. Mechanically critical connections between probes and an electric cable are avoided.

In this paper, a new wireless sensor system is described (referred to as WiSe – Wireless Sensor system) that was developed at the Institute for Marine and Atmospheric Research, Utrecht. The system was specifically designed for deep ice applications and we present the design and first results from two experiments.

The first experiment (hereafter referred to as the Russell experiment) using the WiSe system took place in summer 2010 at Russell Glacier, a land-terminating part of the West Greenland ice sheet margin near Kangerlussuaq. The background for this experiment is a lack of knowledge concerning the role of surface melting in the dynamics of ice sheets and ice caps. In the ablation area, the meltwater partly runs off at the surface and partly reaches the glacier base through crevasses and moulins, where it has the potential to increase basal sliding via increased basal water pressure. The important role of surface meltwater in controlling the motion of valley glaciers has long been recognized (Iken, 1972; Iken and Bindschadler, 1986; Hubbard and Nienow, 1997; Anderson and others, 2004; Harper and others, 2010), but only recently has it been identified as influencing the motion of larger ice caps, and even ice sheets, in Iceland, Svalbard and Greenland (Zwally and others, 2002; Van de Wal and others, 2008; Benn and others, 2009; Sundal and others, 2011). At present, a lack of information on subglacial water pressure hampers a better fundamental understanding of this process. The experiment described was designed to address

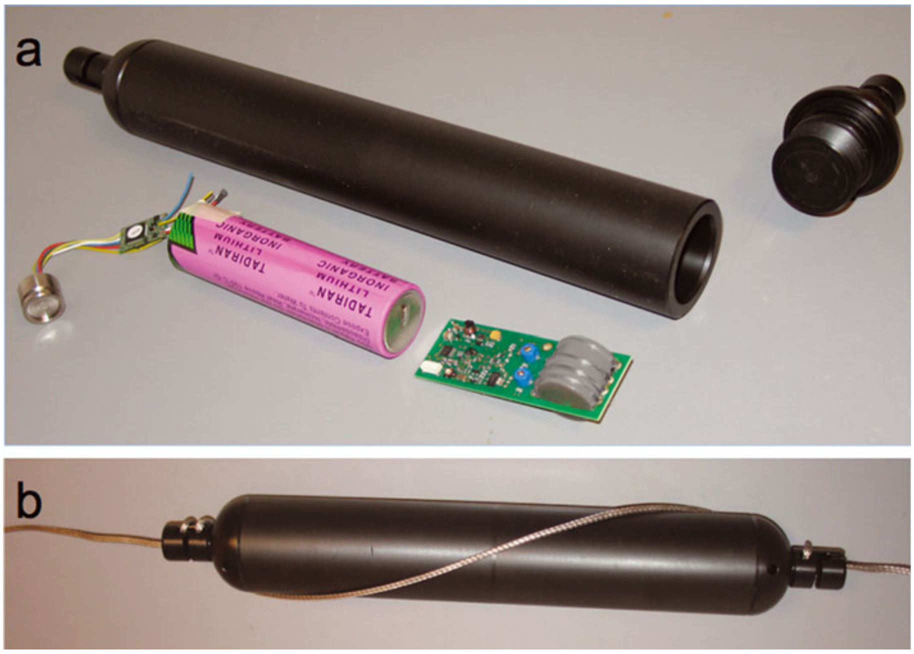

Fig. 1. (a) The probe housing and its internal components (from left to right: pressure transducer, lithium battery, transmitter). (b) A probe attached to the 3 mm Kevlar rope using rope clamps attached at both ends of the housing.

this knowledge gap by combining pressure measurements close to the base of the glacier, five GPS receivers at and around the drill site and an automatic weather station (AWS). The first version of the WiSe system was used to measure subglacial water pressure, borehole inclination and the englacial temperature profile inside two hot-water drilled holes close to the glacier bed.

The second experiment (hereafter referred to as the NEEM experiment) was designed to test the depth range of the wireless system. For the purpose of this experiment three wireless probes were prepared, each with different combinations of transmission power and internal antenna size. In addition, two different receiver antennas were used during the experiment. The experiment took place on 10 June 2011 in the 2537 m deep hole at the drill site of the North Greenland Eemian Ice Drilling project (NEEM).

In the following sections we present the design of the WiSe system, describe the Russell and NEEM experiments and give a summary of the first results.

THE WIRELESS SENSOR SYSTEM: WiSe

During the Russell experiment the first prototype of the WiSe system was used, which was designed to penetrate through thicker ice (up to 1000 m) than the systems presented in earlier publications. Harrison and others (2004) developed a shock-resistant metal probe to hammer into subglacial till measuring pore-water pressure and two axes of tilt through 500 m thick ice using a low-frequency magnetic field for wireless transmission of data. In the GLACSWEB project (Martinez and others, 2004; Hart and others, 2006) wireless probes using a radio frequency of 433 MHz were developed to mimic the movement of stones and sediment under 50–100 m thick ice by means of pressure, temperature and three-dimensional tilt sensors.

Figure 1a displays the custom-made black housing of the WiSe probe and its internal components. The housing is made of the technical plastic, Delrin®, a highly versatile and widely used engineering polymer. It has high mechanical strength and rigidity, excellent resistance to moisture, a wide end-use temperature range, and does not interfere with the transmission of radio waves. The housing of the prototype has an outer (inner) diameter of 50 (40) mm, a length of 300 mm and was designed to resist at least 12 MPa. The probe contains three main components with, from left to right, a pressure transducer, a lithium battery and a custom-made 100 mW transmitter operating at a frequency of 30 MHz. The probes host one sensor at a time, but it is envisaged that future versions will include multiple sensors. Except for the batteries and sensors, all WiSe components (probe transmitter, internal probe antenna, receiver/data-logger system) are developed at an electronic component level in cooperation with a few commercial partners. Hence, no part is commercially available and they are manufactured on request. Depending on the number of probe components, a probe costs between €200 and €500.

The energy consumption of a wireless probe is minimized and in standby mode it uses 6 μA. Each signal transmission takes place at a fixed time interval of ~200 s, lasts 400 ms and consumes 90 mA. For data transfer, on/off keying is used, a popular modulation technique in digital data communication for a large number of low-radio-frequency applications. The source transmits a large-amplitude carrier when it wants to send a ‘1’ and it sends no carrier when it wants to send a ‘0’. This saves energy and ensures a good signal-to-noise ratio. After 10 years of signal transmission the capacity of a single lithium battery (3.6 V, 35 Ah, Tadiran batteries) is ~50%. However, since the manufacturer guarantees a lifetime of 10 years due to self-discharge for this type of battery, we consider a probe lifetime of 10 years to be a safe estimate.

The communication between the probes and the receiver/data-logger system is one-way, i.e. the probe transmits real-time data to the receiver at a fixed interval. To avoid collisions in the transmission of signals between different probes, each probe uses a slightly different interval

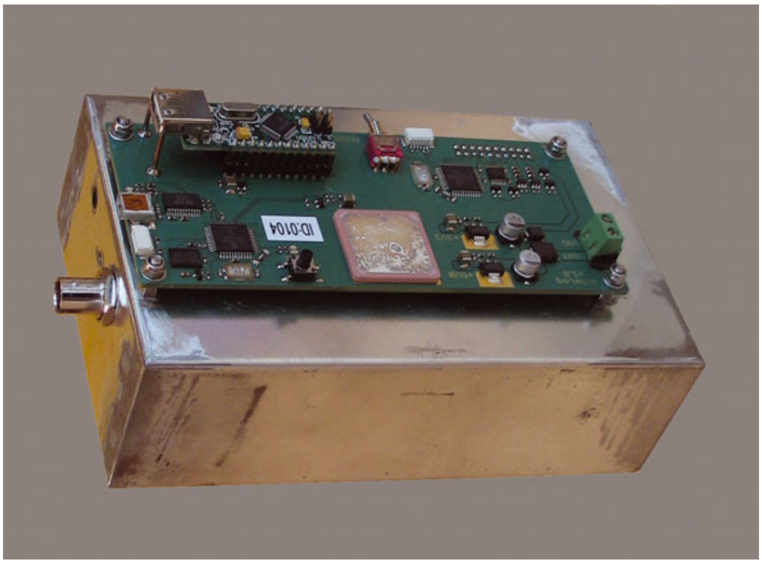

Fig. 2. Photograph of the custom-made receiver of the WiSe system.

ranging between 200 and 220 s at a resolution of 1 s and transmits in one of five different frequency bands (30.038, 30.113, 30.138, 30.163 and 30.213 MHz), with each band accommodating a maximum of 32 sensors. The transmitter inside the probe uses a very compact coil ferrite antenna with a diameter of 28 mm, that is tuned to a frequency of 30 MHz. Ice thickness radar measurements show that a relatively low frequency of 30 MHz has the advantage of increasing the range in most temperate ice conditions, because the resulting wavelength (10 m) is far larger than the size of the majority of englacial water bodies that scatter the signal. Two drawbacks of using this low frequency are that it boosts the size of the transmitter antenna and, while close to the bottom, the signal strength might be reduced more effectively than higher frequencies. During the Russell experiment the receiver/data-logger system was set to monitor a maximum of 32 probes in succession, once every 4 hours continuously for 10 min. The probes transmit 24-bit messages, consisting of a measured variable (e.g. pressure, temperature, inclination) with 14-bit resolution, a 5-bit ID number of the probe and a 5-bit CRC-5 error-detecting code (CRC: cycle redundancy check). This type of error detection is commonly used in digital networks and storage devices and uses a fixed-size single data value that is computed from the data to detect accidental changes to raw data. In the WiSe system, CRC-5 is specifically used to detect errors due to signal collisions. The receiver first checks the integrity of the received data using CRC-5, after which only correct data are stored internally. During a test with a wireless system using 28 probes, the same as during the Russell experiment, it appeared that ~1 in 500 errors pass the CRC-5 check. The data stored in the data logger include the time and position from an internal GPS receiver, transmission frequency, ID number, real-time data, radio-frequency gain, signal strength and noise level. Remote communication via satellite is not yet available and data are retrieved on site using a laptop to download the data directly from the data logger.

The receiver sample interval was restricted to 4 hours because the internal data storage capacity of the first prototype data logger was limited to 8 Mb flash memory, and to reduce the energy consumption of the receiver/data-logger system. The receiver/data-logger system is custom-made and uses a digital synthesizer double superheterodyne receiver type that is powered at 10 V using three lithium batteries (same type as in the probes) for the operation of a full year (Fig. 2). The power consumption during receiving and standby mode is 35 mA and 22 μA, respectively. The receiver/data-logger system is mounted on a small four-legged mast that stands freely on the ice surface (left in Fig. 3a). During the Russell experiment we used two so-called cross half-wave dipole antennas that were mounted on horizontal wooden frames standing freely on the ice to keep them away from the surface (Fig. 3a). A cross half-wave dipole consists of two wires crossing perpendicularly, as depicted in the schematic in Figure 3a, that are inserted inside the bent white plastic tubes on top of the wooden frame.

During the Russell experiment a 3 mm Kevlar rope is used to lower the probes into the hole. During lowering the probes are ‘woven’ into the rope, using rope clamps that are fixed to the outer ends of the probe housing (Fig. 1b), ensuring a strong and quick attachment. Doing so, the probe depth can be adjusted even during the experiment if necessary. To obtain the correct probe depth the rope length was monitored accurately during the experiment.

The sensors that were used inside the probes during the Russell experiment were a piezoresistive pressure transducer from Keller series 10, with an internal 14-bit analogue/digital converter, a range of 0–15 MPa and a resolution of 0.0025 MPa. The dual axis tilt sensor is a MXC6202xJ by MEMSIC, with a resolution of 1.5°. The temperature sensors are ultra-precision thermistors, PR222J2 from US Sensor, with an interchangeable tolerance of ±0.05°C. Note that special care was taken to optimize the temperature measurements. For the temperature range −40 to +10°C a very accurate look-up table was used to faithfully reproduce the resistance/temperature curve of the sensor, reducing these types of errors to <0.01°C. Noise from battery voltage variations and atmospheric interference was minimized by using a resistance bridge measurement and very short connection wires, respectively.

During the NEEM experiment the depth range of the WiSe system was tested for different configurations of probe

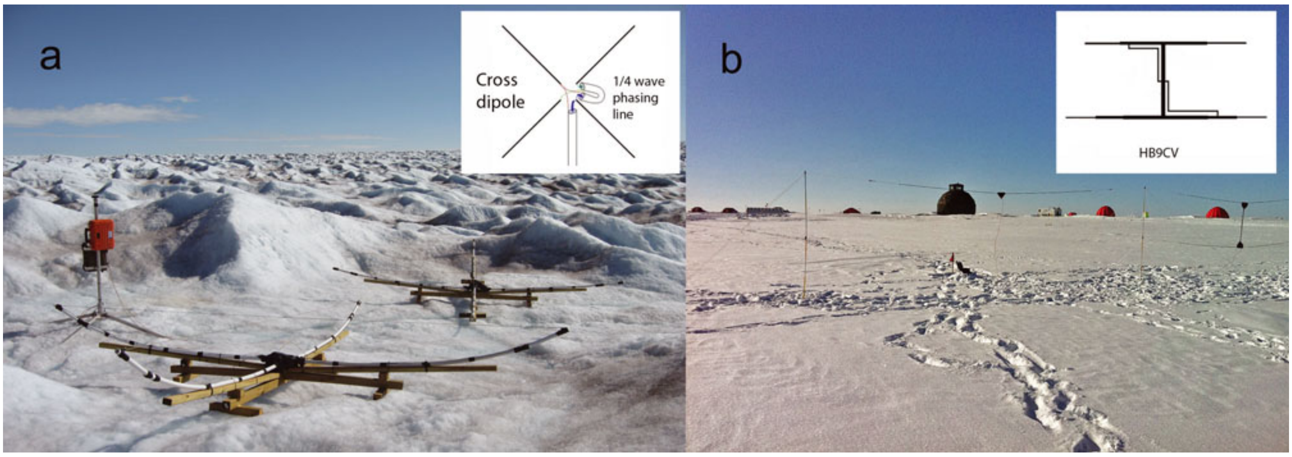

Fig. 3. (a) The two cross-dipole receiver antennas installed at the ice surface at SHR during the Russell experiment in July 2010. On the left is the logger/receiver system on a four-legged mast. Insert shows a schematic of a cross-dipole antenna. (b) The two receiver antennas at the NEEM site in June 2011. On the left the half-wave dipole and on the right the HB9CV antenna. Insert shows a schematic of a HB9CV antenna.

transmission power, internal antenna size and receiver antenna type. Besides the first prototype probe used during the Russell experiment (transmission power 0.1 W) two other probes were prepared. Both had a ten times larger transmission power (1 W instead of 0.1 W) and one of these probes also used a larger internal antenna (57 mm instead of 28 mm). Doubling the coil antenna diameter is similar to increasing transmission power by 50%. The specifications of the different probes and their IDs are given in Table 1.

In Figure 3b the two receiver antennas are shown with, on the left, a half-wave single dipole and, on the right, a HB9CV antenna. Both antennas were mounted horizontally ~1 m above the surface. The HB9CV resembles a log-periodic dipole array with two elements (Fig. 3b, inset) which, compared with a single dipole, efficiently shields from atmospheric noise, thereby increasing the signal-to-noise ratio of the transmitted probe signal. The dimensions of both antennas were tuned to the system frequency of 30 MHz.

EXPERIMENTS

The Russell experiment

The Russell experiment was conducted at site SHR along the K-transect at Russell Glacier, just north of the Arctic Circle (Van de Wal and others, 2005; Van den Broeke and others, 2009). Ever since the K-transect (Fig. 4) was established in 1990, the area has been well studied, providing a long record of mass-balance, continuous GPS and AWS data. Russell Glacier is a land-terminating glacier with high summer ablation rates and supraglacial lake formation/drainage in the vicinity, so it is well suited for studying the effect of meltwater on ice velocity, and isolating it from the potential influence of calving processes. Location SHR lies in the marginal ice zone and was chosen because the summer speed-up there is the largest along the K-transect (Van de Wal and others, 2008).

Table 1. Characteristics and ID of the three different wireless probes tested during the NEEM experiment

ID	Transmitter power W	Coil antenna diameter mm	Relative transmission power
X	0.1	28	1
XL	1.0	28	10
XXL	1.0	57	15

On 9 June 2010, prior to the Russell experiment, ice thickness measurements were performed using ice-sounding radar at nine locations around SHR. At five locations clear bed-return signals were received, which gave a narrow depth range between 565 and 574 m, presuming a radar signal velocity inside the ice of 168 m μs^{-1}. Due to variations in the ice (impurities, air bubbles, liquid water, etc.) a 2% variation in speed can be expected (Navarro and Eisen, 2009). A variation of the depth range of a few meters to ~30 m is therefore likely.

In the period 2–11 July 2010, hot-water drilling and the installation of the WiSe system took place. Two holes were drilled with the hot-water drill from the Alfred Wegener Institute, close to where the ice-sounding radar measurements were performed and ~4 m apart. Given the considerable size and weight of the drill, repositioning of the complete drill system was complicated, so it was decided to move the hose winch a few meters by helicopter. For the hot-water drilling we initially used a narrow pilot drillhead, after which a reamer was used to enlarge the diameter of the hole.

To lower the wireless probes into the holes, we used a tethered balloon winch containing 1000 m of 3 mm Kevlar rope. The first six wireless probes (one pressure, one inclinometer and four temperature sensors) were attached to the rope prior to lowering into the hole. The remaining 22 wireless temperature probes were attached to the rope during lowering into the hole, and by accurately keeping track of the rope length the depth estimate for the first hole is 610 m ± 1 m. Given the small load compared with the rated break strength and the very low potential stretching of Kevlar rope, we estimate that stretching during the experiment was <0.1%, thereby increasing the measured depth by <0.6 m. The wireless pressure and tilt probe were lowered to 0.5 and 24 m above the bottom of the hole, respectively. A temperature profile consisting of 25 probes was installed at a distance of 1.5, 5.5, 10.5, 15.5 m and continuing

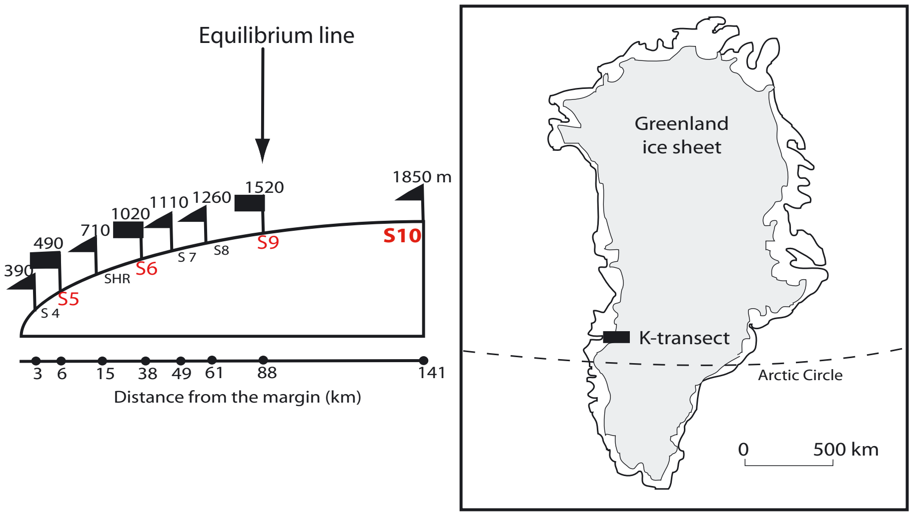

Fig. 4. The location of the K-transect in the ablation area of the West Greenland ice sheet, together with a cross section showing the names, heights and distance from the ice edge for each site. The locations of the AWSs are marked red.

at intervals of 25 m to a distance of 551.5 m from the bottom and 58.5 m from the ice surface. After installation it appeared that the transmitter inside the temperature probes at 584.5 and 209.5 m below the ice surface malfunctioned for unknown reasons. In hole 2 we installed one wired probe (i.e. connected to the surface via an ordinary serial/power cable) with a pressure and temperature sensor inside and one wireless probe with a pressure sensor at ~0.5 m above the bottom. Unfortunately, the pressure sensor inside the wireless probe malfunctioned during the descent. Using the pressure difference between the wireless and wired measurements, the depth of hole 2 was estimated to be 632 ± 1 m. The depths for both holes are consistent with the depth plumbing measured with the drill.

A total of 28 wireless and 1 wired probe were installed in two 600 m deep holes. Two wireless transmitters from probes containing temperature sensors and one pressure sensor inside a wireless probe malfunctioned. The first dataset from the receiver/data-logger system was retrieved in August 2010. At that time the wireless system was operating as it was left in July 2010, and we present data from 6 July to 17 August 2010 in the Results section. At the time of writing, the wireless system was still operational, and the latest dataset was retrieved in September 2011, covering a period of >1 year. A gap in the wireless data exists from the end of the winter to the beginning of summer melt (18 March to 8 June 2011) due to an empty battery pack in the data-logger/receiver system.

The NEEM experiment

During the NEEM experiment, the winch from the NEEM ice-core drill was used to lower the probes inside the hole. The influence on the signal transmission of metal wires between the probes and the receiver was tested. The first test was performed during the Russell experiment, where a wireless and wired system were installed next to each other in two holes only 4 m apart (previous subsection). The wireless system was installed first, and during the lowering of the wired system in the second hole no change in the signal strength from the wireless probes was monitored. The second test was performed in April 2011 at a Swiss skiing station near Pontresina. The transmitting probe was located close to the top station (2960 m a.s.l.), while at the ground station (2100 m a.s.l.) the receiver was positioned at various distances from the cable. The wires from a large gondola lift hang at a considerable distance from the earth surface between the ground and top station and mimic the situation in ice. During this test, weakening of the transmitted signal was only observed when approaching the cable-car wire closely (within 10 m). Moving the receiver away from the ground station at considerable distances by car showed a gradual weakening of the signal strength, as expected from increasing the distance between transmitter and receiver. The results from these two tests are robust, and indicate no interference of a metal wire with the signal transmission; it was thus deemed safe to use the steel ice-core drill cable for lowering the probes.

The three wireless probes (Table 1) were attached to Kevlar rope with 3 m between them, while the upper probe was separated from the wire of the winch using 25 m of Kevlar rope. This is comparable to approximately four wavelengths in ice at 30 MHz, and should suffice to exclude any energy transmission between the probes and the wire. At the surface, comparable measurements were taken to avoid energy transmission between the drill wire and the WiSe receiver antennas by installing them 100 m away from the ice-core hole. Mounting the surface antennas horizontally, hence, perpendicular to the ice-core drill wire, additionally helps to reduce such influences.

OVERVIEW OF FIRST RESULTS

Russell experiment: pressure data

Figure 5a displays the first 6 weeks of wireless and wired pressure data from the Russell experiment. The agreement between the two time series is very good, with no data gaps, thereby demonstrating that the wireless system is capable of continuous data transmission through 600 m thick ice. For a proper comparison of data between the time series, we only selected simultaneously measured data using a time window of 30 min. Hole 2 was ~22 m deeper than hole 1, which was corrected for by offsetting the wireless pressure data by +0.22 MPa. Figure 5b shows the difference between the two time series, for which the average and standard deviation

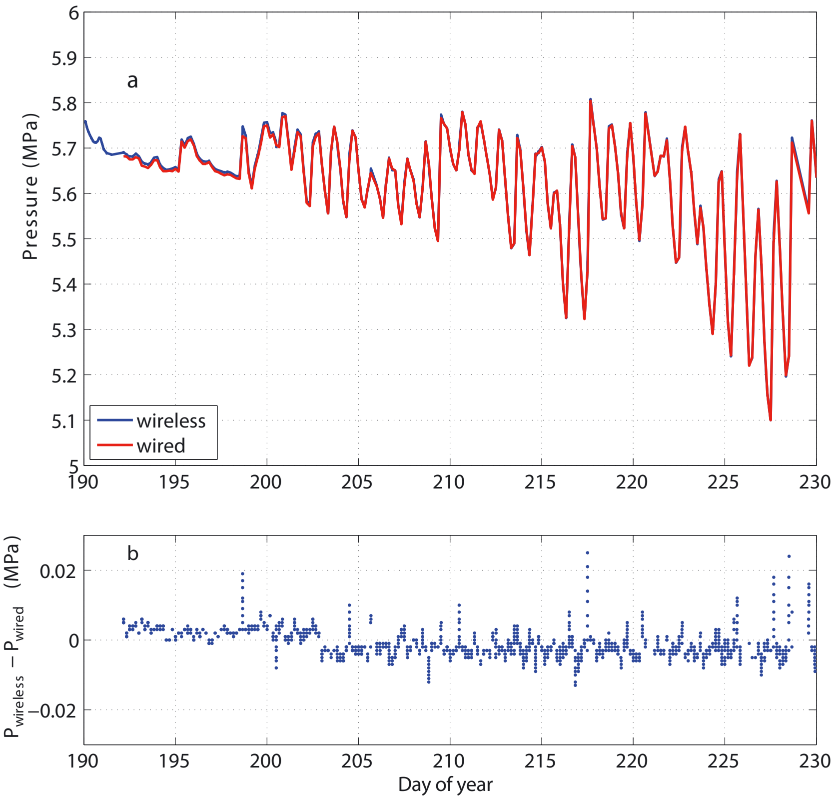

Fig. 5. (a) Data from the wireless (blue) and wired (red) pressure probes and (b) the difference between the two pressure signals.

are 0.002 and 0.004 MPa, respectively. The small random differences are explained by subglacial pressure variations within the 30 min time window applied. Note that at the end of day 202 the pressure of the wired probe dropped ~0.006 MPa, which probably relates to a 0.6 m increase in depth of the wired probe due to a sudden displacement of the wooden anchor at the ice surface as a result of strong surface melt.

Russell experiment: temperature and tilt data

Unlike the pressure data, the wireless temperature measurements cannot be compared with a measured reference. Instead, the melt-point temperature of the water inside the hole directly after installation of the probes is used as a reference. In Figure 6a the average temperature profile measured shortly after installation of the probes (day of year (DOY) 190–192) is plotted as a function of depth below the water level in hole 1. The theoretical reduction of the melt temperature with depth is represented by the curves for air-free (solid line) and air-saturated water (dashed line). It should be noted that soluble impurities in the water can alter these curves substantially (i.e. impurities lower the melting point; Paterson, 1994). In general, the wireless temperature data follow the theoretical curves within a range of about ±0.1°C, which is in part explained by the accuracy of the thermistor type used.

Studying the individual time series shows that the lowest 15 probes (611–310 m below the ice surface) behave the same, i.e. small daily temperature variations 180° out of phase with those of subglacial pressure. As an example, the time series from probe No. 13 at 287 m (blue dot in Fig. 6a) below the water level is plotted together with subglacial pressure as a function of time in Figure 6b. A decreasing subglacial pressure leads to an increasing probe temperature, in accord with the curves in Figure 6a. Although the signal is very small it is reproduced by all 15 probes simultaneously, thereby demonstrating the excellent precision of the temperature measurement system inside the probes. It is also proof that the lowest 15 probes were immersed in water throughout the period. In contrast, all probes 310–110 m below the ice surface show a gradually decreasing temperature with time, probably as a result of contact with the wall of the hole. The two uppermost probes (110 and 60 m below the ice surface) show, in part, daily variability in line with subglacial pressure data as well as periods when the water column inside the hole dropped below their level.

The above data provide confidence in the operation of all temperature probes of the WiSe system and demonstrate the good accuracy and precision of the temperature measurements inside the probes.

The data from the tilt sensor, which was fixed at ~25 m above the bottom of hole 1, cannot be tested against a reference but were received in good order. The directional data do not vary in time during the entire period but show constant values of +11° and −5° besides some noise (±1°). The relatively large angles result from inaccurate placement of the electronics inside the probe, while the noise is in accord with the specifications of the sensor.

NEEM experiment

During the experiment at NEEM on 10 June 2011, the three probes were slowly lowered into the hole (10 cm s^{-1}) to avoid rope entanglement and wall collisions due to buoyancy of the probes in the drilling fluid. The probes were lowered until close to the bottom of the hole at ~2510 m. During

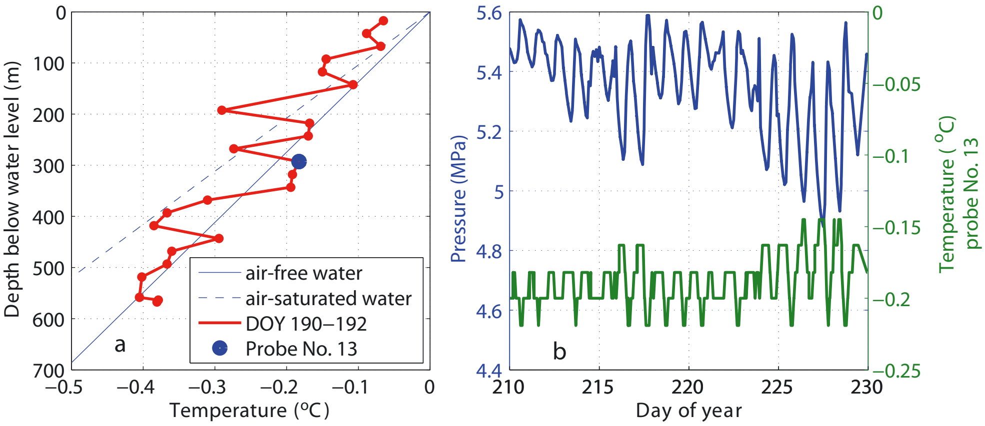

Fig. 6. (a) The average temperature profile (red) in hole 1 for the period DOY 190–192, as a function of depth below the water level, together with the theoretical curves for the melting point of air-free and air-saturated water (solid and dashed blue lines, respectively). (b) Time series of pressure at the base of the glacier (blue) and temperature from probe No. 13 (green; blue dot in (a)) at 287 m below water level in hole 1 as a function of time.

lowering, the half-wave dipole surface antenna was used to receive the probe signals. Before going up, the HB9CV antenna was connected (Fig. 3b). In Figure 7 the main characteristics of the signal strength from all three probes inside the NEEM hole are plotted as a function of depth (see Table 1 for probe IDs). For the downward and upward sections, solid and dashed curves are used, respectively. To distinguish between the different signals, they are artificially offset. During lowering of the probes the signal strength of probe X (green solid) starts to decrease around 1400 m and vanishes around 1700 m, while for the XL and XXL probes it starts to decrease at 2100 and 2200 m, respectively. Nevertheless, the signal-to-noise ratio for the latter remains sufficient for a proper reception of the data through 2500 m thick ice. Switching from half-wave dipole to the HB9CV antenna restores XL and XXL signals to a high signal-to-noise ratio. Varying the transmitter power and the receiver antenna type appears to be far more effective for increasing the range of the WiSe system than varying the internal antenna characteristics. The results collected during the NEEM experiment demonstrate that the WiSe system can transmit data through 2500 m thick ice.

CONCLUSIONS

We have presented the design and first data from two experiments performed with a newly developed wireless subglacial sensor system (WiSe) that is shown to transmit data through 2500 m thick glacier ice. The first field test with the system was performed in July 2010 at Russell Glacier. Two holes (610 and 632 m) were drilled close to the bed, in which we successfully installed an array of 25 wireless probes (one pressure and one tilt sensor near the bottom of the holes and a vertical profile of 23 temperature sensors) next to a reference system consisting of a wired pressure/temperature sensor.

Data retrieved during our first visit on 17 August 2010, 6 weeks after the start of the measurements, demonstrated that subglacial pressure from the wireless and wired reference system are equal to within 0.005 MPa. The wireless temperature measurements cannot be compared with a measured reference; instead the variation of the melt-point temperature inside the water-filled hole was used directly after the installation of the probes. In general, the temperature data follow the theoretical curves for air-saturated and air-free water. Small random excursions (±0.1°C) between the data and the curves in part result from the measurement accuracy of the type of temperature sensor used.

The latest data retrieval from the Russell experiment took place in September 2011, showing that the wireless system is still operational, and has now been collecting data from 25 wireless probes for >1 year.

In order to test the maximum depth range of the WiSe system, a 1 day experiment was performed in June 2011 in the ice-core hole at the NEEM site, using three different types of probes and two different surface antennas. Using the most sensitive surface antenna, the maximum depth attained with the first prototype probe (0.1 W transmitter power) was 1700 m. Two specially prepared probes, both with increased transmitter power (1 W) and one with a larger internal antenna, transmitted data at a high signal-to-noise ratio through 2500 m thick ice.

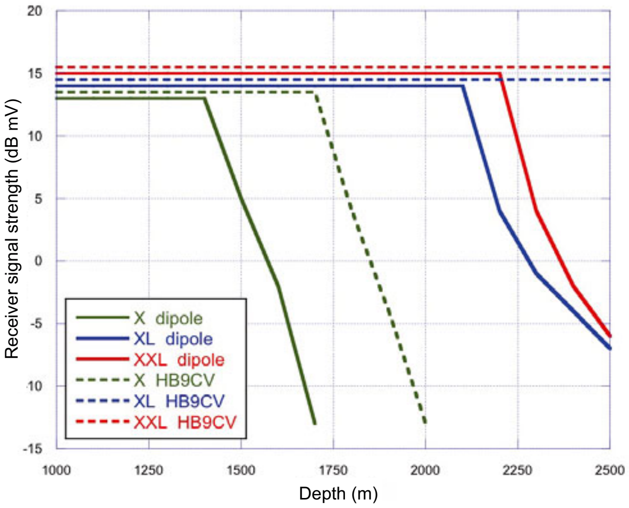

Fig. 7. Receiver signal strength as a function of depth from three probe types during the NEEM experiment. A half-wave dipole and a HB9CV receiver antenna were used while moving the probes down (solid curves) and up (dashed curves) inside the hole, respectively.

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