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M. Len Keeler
University of Minnesota, Morris

Keith A. Brugger
University of Minnesota, Morris

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Instruments and Methods

A method for recording ice ablation using a low-cost ultrasonic rangefinder

M. Len KEELER,[1] Keith A. BRUGGER[2]

[1]*Physics Discipline, University of Minnesota, Morris, MN, USA*
E-mail: keelerm@morris.umn.edu
[2]*Geology Discipline, University of Minnesota, Morris, MN, USA*

ABSTRACT. We have adapted inexpensive ultrasonic rangefinders to measure ablation rates on the surface of a glacier. While ultrasonic rangers are commercially available for this purpose, our goal was to utilize rangefinders typically used in hobby robotics without significantly compromising performance. To correct for environmental factors that affect the speed of sound we use two ultrasonic rangefinders, one focused on a fixed target. Measurements of ablation correlate well with manual measurements with an uncertainty of about ±3 cm, suggesting an accuracy comparable with other non-manual methods of recording ablation. The limitations of our rangefinder include those inherent in commercially available units as well as having less acoustical power, which results in a reduced effective range of the sensor (~2 m) and difficulties in detecting surfaces lying below low-density snow. Our sensor design provides a cost-effective means of increasing the spatial coverage of ice ablation measurements.

INTRODUCTION

Glaciers respond dynamically to changes in their mass balance caused by climatic variations. Thus as the driver of glacier fluctuations, there is considerable interest in accurately quantifying mass-balance components. Moreover, variations in glacier mass balance have been used directly as climate proxies (e.g. Dowdeswell and others, 1997; Dyurgerov and Meier, 1997; Vincent and others, 2004). Measurements of ablation, in particular, are important in developing and/or calibrating models of snow and ice melt based on energy-balance or temperature-index approaches (e.g. Braithwaite, 1995; Hock, 1999; Schaefli and others, 2005; Anslow and others, 2008). Such models are useful in numerical simulations of glacier behavior (e.g. Oerlemans and others, 1998), in estimating the contribution of glacier melt to sea-level changes (e.g. Raper and Braithwaite, 2006) and in assessing the impact of climate change in glacierized basins on runoff production and water resources (e.g. Hagg and others, 2007; Huss and others, 2008; Stahl and others, 2008), among other applications.

Despite their value, measurements of ablation (and accumulation) are frequently limited by time, labor and fiscal constraints, the size, remoteness or accessibility of the glacier and so forth (Fountain and Vecchia, 1999; Fountain and others, 1999). Therefore to augment or replace the traditional ablation stakes methodology a number of alternatives for on-glacier measurements (as opposed to remote measurements) have been developed. These include a variety of ablatometers (Müller and Keeler, 1969; Munro, 1990; Bøggild and others, 2004; Hulth, 2010) and ultrasonic rangefinders.

Here we present instructions for the construction of a low-cost ultrasonic rangefinder for measuring ice ablation that has an accuracy comparable with commercially available units. The idea is to capitalize on the low cost of sensors and compensate for humidity, wind, temperature and electronics by simply utilizing a second sensor unit as opposed to making separate measurements of environmental factors, and then applying either an analytical or empirical correction. Compared with commercial rangefinders, the transducer used in our sensor has lower acoustical power and consequently a shorter useful range (~2 m versus 10 m) and a narrower effective beam angle. Lower power also means performance may be compromised when the ice surface is covered with very low-density snow from which there is a weak return of the ultrasound pulse, a shortcoming shared to some extent with commercial units (Campbell Scientific, 2011). Nevertheless the attractiveness of our design lies in its ability to provide accuracy rivaling commercial sensors at a significantly lower cost (US$175 versus US$600–1000, and in some cases the latter excludes a temperature sensor and/or data logger). The functional accuracy (i.e. under field/site conditions) of our sensor is estimated to be of the order of ±3 cm. Although the stated accuracy of, for example, the Campbell Sonic SR50A Ranging Sensor or Judd Communications Ultrasonic Depth Sensor is ±1 cm (Campbell Scientific, 2011; http://juddcom.com/#Depth), the functional accuracy inferred from studies wherein the raw data of ultrasonic measurements are presented (e.g. Bøggild and others, 2004) is probably slightly larger and therefore suggests the accuracy of our sensor compares even more favorably with commercial units.

INSTRUMENT AND SET-UP

Our design is centered on the PING™ ultrasound rangefinder manufactured by Parallax which retails for about US$30. A stake, the basis for a simple mast arrangement, is set in the glacier surface. One ultrasound ranger is fixed on the glacier surface while a second is fixed on a target of known distance (Fig. 1). The microprocessor and batteries are contained in a weatherproof housing constructed from PVC pipe. The PING™ rangefinder is a three-terminal device that requires a 5 V supply voltage, ground and a

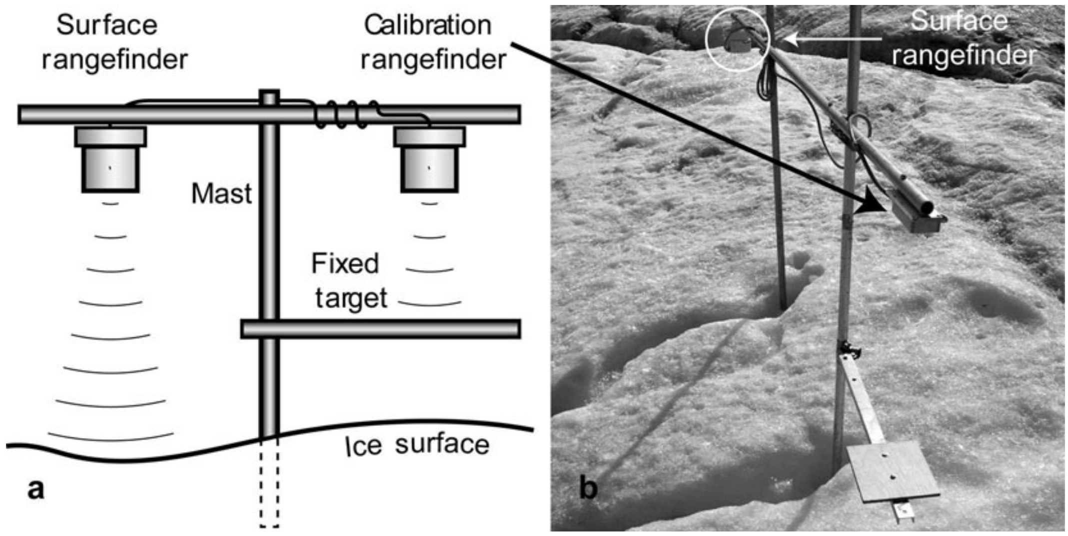

Fig. 1. (a) Schematic diagram of mast with ultrasound rangefinders. The housing containing the surface rangefinder also contains the microprocessor/data logger. (b) Photograph of unit in operation on Storglaciären, Sweden.

trigger pulse. The trigger pulse causes the rangefinder to emit a short burst of ultrasound waves around a 40 kHz carrier frequency. After detecting a reflected signal, the rangefinder returns an electrical pulse the length of which is equal to the echo time (time for the ultrasound pulse to travel to and from the target).

Because it is widely used, well documented, contains built-in non-volatile memory and will operate at temperatures as low as –40°C we chose to use the Parallax BS2-IC to serve as the microcontroller and data logger. Other hobby-geared microprocessors such as the Arduino and PicAxe are less costly and with additional development may also be adapted as controllers. The unit was designed to work with standard 9 V lithium batteries (1200 mA h) the chemistry of which enables the battery to deliver power even at low temperatures. The BS2 microprocessor is programmed to remain in 'sleep' mode between measurements. In this mode the BS2 draws ~50 μA, and with a dedicated 9 V battery it is estimated that the unit will run for almost 3 years. The ultrasound ranger draws about 40 mA during operation and

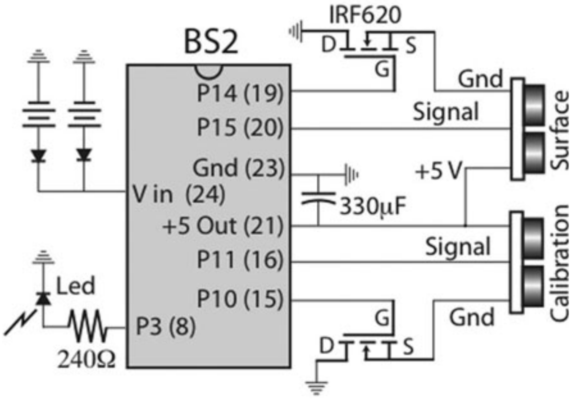

Fig. 2. Schematic diagram of circuit. 9 V lithium batteries are used to power the BS2 microcontroller, which in turn supplies the 5 V power for the two ultrasonic rangefinders. Multiple batteries can be used to extend the battery life of the unit as long as they are isolated through diodes. Numbers in parentheses indicate the pin number on the BS2-IC; PX indicates the output or input 'port' number.

this necessitates that the microprocessor be able to selectively activate power to the units just prior to a measurement. We use IRF620 field-effect transistors (FET) (available through most secondary electronics distributors) to act as switches for the ultrasound ranger power. The critical parameter for these FET switches is that they be n-channel enhancement-mode switching transistors. While the BS2 microprocessor has an on-board regulator that can supply the 5 V (maximum current of 40 mA) for the ultrasound units, moments of high current draw can cause temporary fluctuations in the supply voltage. For this reason, an electrolytic capacitor is used to store charge and filter the 5 V regulator output. To ensure operation for long periods of time under potentially cold or humid conditions, all exposed circuit elements, leads and traces were protected with a clear varnish. A schematic of the final circuit is shown in Figure 2.

The BS2 is programmed with a form of the basic programming language and there are significant online resources and tutorials devoted to programming the processor. The following is a brief description of the program flow. Upon resetting, the data acquisition program (stored in the non-volatile EEPROM memory) sends a signal to the output pin 8 (P3) to visually confirm operation via the light-emitting diode, then starts a time delay before taking data. The processor is programmed to 'wake up' and take data at regular 4 hour intervals. It takes a calibration measurement by first activating the calibration sensor (sending a signal out to output pin 15, or P10) and then starts an ultrasound ranging measurement by sending a short pulse to the signal pin of the ultrasound ranger (short pulse out on pin 11, P16). The ultrasound ranger then returns a pulse the length of which is equal to the round trip time of the ultrasound pulse. This pulse length is measured by the microprocesser on pin 11, then recorded in the built-in non-volatile EEPROM memory as a two-byte 'word'. The process described above is repeated for the ultrasound ranger directed at the glacier surface. Several refinements have been made to the basic program described above. One is that the ranger first checks to see if there is a nonzero value written to the EEPROM before writing data. This prevents data from being accidentally written-over in the case of a programmatic reset that can be initiated in the event of a significant power

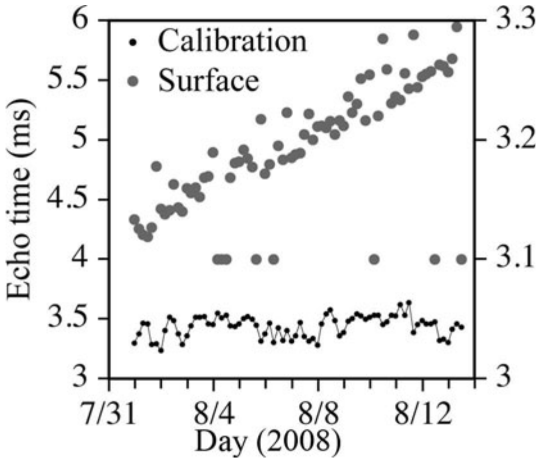

Fig. 3. Raw round-trip time. Left-hand scale is the return time for the pulse directed towards the glacier surface (large gray data points) while the right-hand scale is used for the calibration data (small black data points). Date format is month/day.

fluctuation. In addition, noisy conditions due to wind could cause false measurement results and the microprocessor could be programmed to look for these and take multiple measurements if necessary. Finally, multiple measurements could be taken and averaged before recording the final result. One limitation of the BS2 microprocessor is the amount of volatile RAM available for programming and data storage (2 kB), which can be remedied by using similar modules with higher memory capacity.

DATA

Two prototypes were deployed on Storglaciären, Sweden, in order to record ice ablation during the 2008 melt season. Manual measurements of the change in the ice surface were also made for comparison. This section details the procedure used to convert and process the raw data stored within the data-logger flash memory. The microprocessor records the pulse length in units of 2 μs, and multiplying this by 2000 gives the round-trip time (ms) (Fig. 3). The calibration target was fixed 50 cm away from the calibration sensor and the associated round-trip time varied from 3.064 to 3.024 ms, with a mean of 3.044 ms. These measurements correlate to sound velocities of 326.3, 330.6 and 328.5 m s^{-1}, which is consistent with the approximate value of 331.3 m s^{-1} (speed of sound at 0°C). Fluctuations observed in the calibration data, particularly within the first 3 days, are indicative of warmer air during the day and cooler air at night. These calibration measurements account for all systematic variations in the data including ambient effects on the speed of sound (temperature, wind speed, pressure, humidity) as well as temperature dependencies in the rangefinder electronics.

Acoustic noise generated from winds, low temperatures or low surface reflectivity can cause false or non-measurements to be made. False data (times corresponding to <10 cm or >10 m distances) were recorded intentionally and 'marked' as the exact value of 10 000 and removed before final analysis. Individual data points were compared with a running 24 hour average, and points that deviated from the running average by more than the average standard deviation were also eliminated from the dataset. Once statistical outliers were removed, the calibration data were used to determine the effective sound velocity and this was used to convert the echo time from the glacier surface to a calibrated distance. Figure 4 shows the results of this analysis, along with the results of the manual measurements. Direct comparison of Figure 4 with Figure 3 illustrates the collective results of corrections for removal of statistical outliers and all environmental factors accounted for by the second sensor. The average standard deviation can be approximated by assuming that the variation between measurements taken within 4 hours of each other is dominated by the measurement uncertainty. For the ultrasound data logger we found a standard deviation of 2.34 cm in our measurements and a total ablation measurement of 23 ± 3.3 cm. Manual measurements of the distance between the rangefinder and glacier surface were also taken when possible, and resulted in a total ablation measurement of 27 ± 2.7 cm. It is worth mentioning that at sensor locations the microtopography of the ice surface was irregular, with amplitudes of surface roughness being typically of the order of 2–3 cm. Linear regressions on both datasets returned average ablation rates of 1.84 ± 0.56 cm d^{-1} (ultrasound) and 2.00 ± 0.3 cm d^{-1} (manual), where the uncertainty in the slope is determined by a reduced χ^2 test.

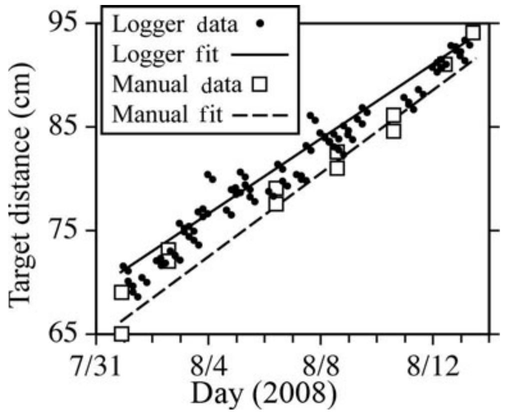

Fig. 4. Data-logger and manual measurements of the rangefinder to glacier surface distance. Linear regressions on both datasets return ablation rates in cm d^{-1}. Date format is month/day.

NOTES ON SNOW ACCUMULATION

We had also intended this instrument to be sensitive to snow accumulation. For this measurement a snow shield is used to prevent accumulation on the calibration standard. We found that ultrasound pulses were poorly reflected from unpacked (and/or low-density) snow and that the rangefinder failed to make measurements from surfaces with a layer of freshly fallen snow. The accumulation would eventually be read after significant surface melting (and/or densification) occurred. Then, counter to expectations, we would often measure accumulation after periods when the ambient temperature exceeded 0°C. Thus for snow surface measurements the device needed to be fitted with a more powerful ultrasound transducer and driver electronics. Regardless of this shortcoming, however, testing over several winter months in Minnesota indicates that the sensor can still be useful if one is not interested in the exact timing of accumulation events but rather in recording total accumulation after sufficient densification has occurred and/or changes in older (i.e. at the onset of the melt season) snow surfaces.

SUMMARY

We have constructed an inexpensive ultrasonic ranging sensor that accurately measures ice ablation but could also be used in other applications. Environmental factors that affect the transmission of sound are corrected for by a second sensor aimed at a fixed target. Variations in these factors, particularly temperature, could be insignificant in their effects over short timescales and the second sensor can be omitted. However, over a typical ablation season (or under other circumstances) corrections for these variations might be required to ensure the accuracy of ablation measurements, for example when the ambient temperature range changes considerably over the duration of the melt season. Given that the cost of a second sensor is minimal, its inclusion might be desirable. Based on tests conducted during harsh Minnesota winters, if the sensor enclosure is sufficiently 'hardened' it will operate reliably for months. Although the sensor can be used as a stand-alone instrument, we see its primary purpose as augmenting commercial units in order to increase the spatial measurements of ablation over an entire glacier's surface and/or more accurately quantifying ablation over a more limited area or 'point' that can sometimes be problematic (Braithwaite and others, 1998).

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