SNOW DEPTH MEASUREMENT USING ULTRASONIC SENSORS AND TEMPERATURE CORRECTION

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ABSTRACT

Snow depth is commonly measured by visual observation, thus limiting the availability and frequency of observations in remote areas. Ultrasonic depth sensors can overcome this limitation by allowing automated snow depth measurement at remote, unstaffed sites. An ultrasonic sensor determines the distance between a surface and itself by measuring the transmission time of a sound pulse reflected off the surface. The sensors are used in industry and water resources management for a variety of purposes. Measurement errors arise both from temperature-based changes in the speed of sound and from the effect of temperature on the electronics of the sensor. These problems may be reasons that the instruments have not seen widespread use in snow hydrology. We installed two sensors, one with on-board temperature compensation and one without, to follow changes in snowpack depth during the winter of 1993 in California's Sierra Nevada. Sensor depths agreed well with daily visual observations, but depth fluctuations, measured quarter-hourly, were evident with both sensors and correlated to changing air temperature. Air temperature was measured independently at the site, and two algorithms were designed that used air temperature or air and instrument temperature to remove the spurious depth fluctuations.

INTRODUCTION

Precipitation, air temperature, and snow water equivalent (SWE) are commonly measured parameters at remote, unstaffed weather stations throughout snow zones in the west. Snow depth, however, is measured infrequently at remote sites. Lack of snow depth information is a limiting factor to site managers who need a real-time understanding of snowpack response to snowfall, rainfall, and melt. By combining snow depth with SWE, site managers could estimate average snowpack density. Density information can be important in the assessment of flow pulses, outflow timing, and the water-holding capacity of the pack.

From February 4 through June 1, 1993, we tested two ultrasonic distance sensors, installed and calibrated for automated snow depth measurement. The sensors measure the time required for a sound pulse to travel to the snowpack surface and return to the sensor. But because the sound pulse is a mechanical wave, its speed is affected by changes in the medium though which it travels. Fluctuations in air temperature and air density can introduce errors into the distance data. Other factors can influence the quality of an ultrasonic sensor's reflected wave pulses, including the hardness of the target surface, the distance to the target, the size of the target, interference by falling snow, and the angle at which the waves strike the target. The snowpack surface in a large clearing provides a large and relatively flat target.

The objective of this study was to devise a method to compensate for the temperature effects on distance measurement by ultrasonic sensors. Of the two sensors installed, one compensated for temperature effects internally (Sensor B), and one did not (Sensor A). We measured air temperature and the temperature inside the plastic pipe that housed the sensors, and used these data to develop algorithms that reduced the erroneous measurements of depth, caused by fluctuations in temperature, in both sensors' depth data.

STUDY SITE AND SENSOR INSTALLATION

The sensors were tested at the Pacific Southwest Research Station's Central Sierra Snow Laboratory (39°19'26" N, 120°22'00" W, 2100 m) near Lake Tahoe, California. The sensors were manufactured by Lundahl Instruments, models DST (Sensor A) and DCU-7 (Sensor B)*. Both sensors are cased in stainless steel cylinders 59 mm in diameter; Sensor A is 89 mm long, and B is 133 mm long. The sensors require 12-24 volts DC. We mounted both inside short pieces of PVC pipe with a diameter of 6.35 cm (2.5 in), oriented vertically and pointing downward, 4.66 m above level ground (Figure 1).

The PVC was attached to a horizontal steel pipe fastened to the main instrument tower at the CSSL. An Omnidata model ES-060* thermistor was affixed inside the pipe to allow comparison of pipe (sensor) temperature to actual air temperature measured by an aspirated platinum-resistance thermistor mounted 1 m above the snow surface and 4 m from the sensors. The master snow stake at the CSSL, where daily visual observations of snow depth are taken, is 3 m from the area targeted by the ultrasonic sensors. Visual observations of snowpack depth were recorded to the nearest 0.5 cm. We assumed the ultrasonic sensors were both measuring the same patch of snow, but a minor difference in depths might occur. Also, we assumed that our individual sensors are typical of average sensor performance. Cost and mounting considerations prevented us from replicating the sensors.

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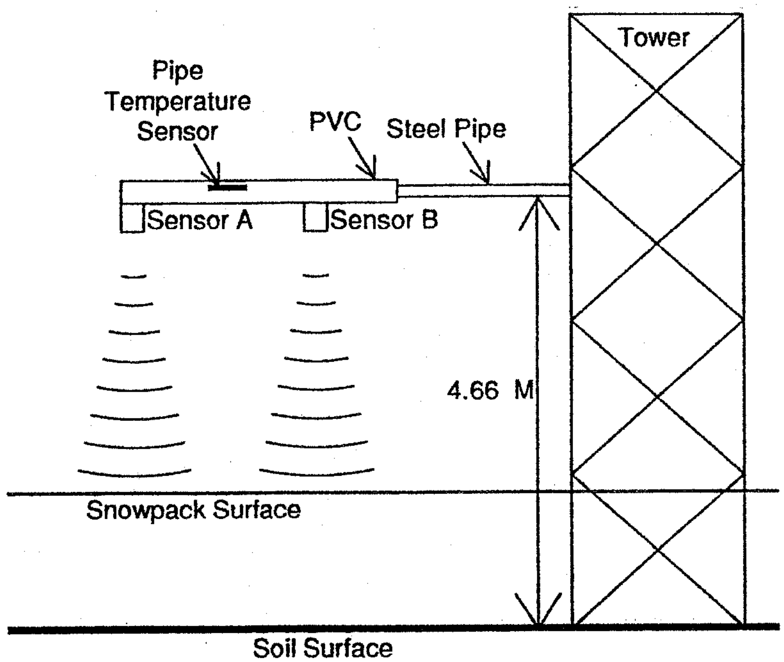

Figure 1. Mounting schematic of Sensor A, Sensor B, and pipe temperature sensor.

Data from both ultrasonic sensors, pipe temperature, and independent air temperature were recorded by an Omnidata model EL-824* data logger at five-minute intervals, and the averaged data were logged every 15 minutes. The sensors were turned on 0.5 seconds prior to measurement, and the scan length was 0.25 seconds.

Sensor A was connected to a programmable controller with a liquid crystal display (Lundahl model DCR-1A*) inside the CSSL. This controller averages and processes incoming signals to reduce false "noise". When Sensor A was queried, the snow depth could be read directly off this display and the output in units of volts was recorded by the data logger. Because Sensor B is self-contained, costs less, and compensates for temperature, we presumed that it was the device most likely to be used at a remote site. The following equations convert the raw data (output 0-5 volts) into centimeters:

$$\text{Snow Depth (cm)}_{\text{Sensor A}} = (\text{Volts}_{\text{Sensor A}})136.65 - 112.56 \quad (1)$$
$$\text{Snow Depth (cm)}_{\text{Sensor B}} = 466 - (\text{Volts}_{\text{Sensor B}})97.54 \quad (2)$$

Equation (1) was derived from a linear regression calibration between observed depth values at the master snow stake and concomitant voltages, and has a coefficient of variation equal to 0.96. Equation (2) was supplied by the manufacturer.

TEMPERATURE EFFECT AND COMPENSATION

Differences may be observed between the pipe and air temperatures during a warm, clear spell in early May (Figure 2). During early morning and late afternoon the two match closely, but discrepancies are evident during the warmest hours of the day. As expected, the late-morning sun caused the air in the pipe to heat quickly, and to a higher temperature than that of the outside air. This temperature differential was correlated to mid-day fluctuations in the sensor depth data. Reradiation from the PVC and steel tower at night may explain the slightly lower pipe temperature during the coolest hours.

The uncompensated Sensor A data reflect the increased speed of sound through warm air as an increase in snow depth (Figure 3a). After some graphical trials, actual air temperature was used to develop a correction equation:

$$A' = 466 - (466 - A)x \quad (3)$$

where

A' = the corrected snow depth (cm) measured by Sensor A,
A = snow depth (cm) measured by Sensor A,
$x = [(273 + T_{air}/2)/273]^{1/2}$,
T_{air} = air temperature at 1 m above snow surface (°C).

These corrected data are also displayed in Figure 3a. The constants 466 and 273 in the above equations refer to the height at which the sensor is mounted and Celsius-to-Kelvin conversion, respectively. During peak solar radiation, Sensor B (which compensates internally for temperature) tends to under-measure the snowpack depth (Figure 3b), as it measures a higher-than-actual air temperature and mistakenly uses a larger value for the velocity of sound in its

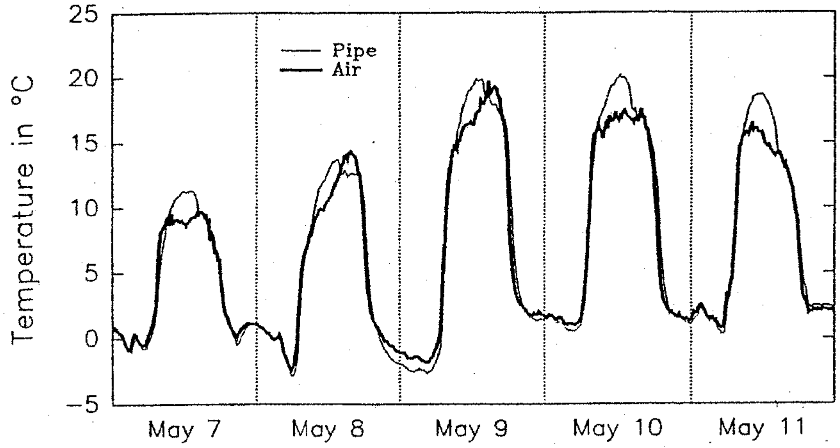

Figure 2. Comparison of actual air temperature and pipe temperature during warm, clear weather in early May, 1993, at the Central Sierra Snow Laboratory, Soda Springs, California. Differences were correlated to fluctuations in depth data.

correction equation. To minimize the false depth fluctuations from Sensor B, after some graphical trials we developed and applied a second correction equation:

$$B' = 466 - (466 - B)x/y \qquad (4)$$

where

B' = the corrected snow depth (cm) measured by Sensor B,

B = snow depth (cm) measured by Sensor B,

$y = [(273 + T_{pipe})/273]^{1/2}$,

T_{pipe} = pipe temperature (°C).

Equations (3) and (4) are based in the physics of sound transmission and were effective in removing the gross fluctuations from the data. For the time period in Figure 3, regression lines were fitted to the data from both sensors both with and without temperature correction. For Sensor A, the sums of squares around the regression line with temperature correction decreased to 39% of the uncorrected sums of squares. Similarly for Sensor B, the sums of

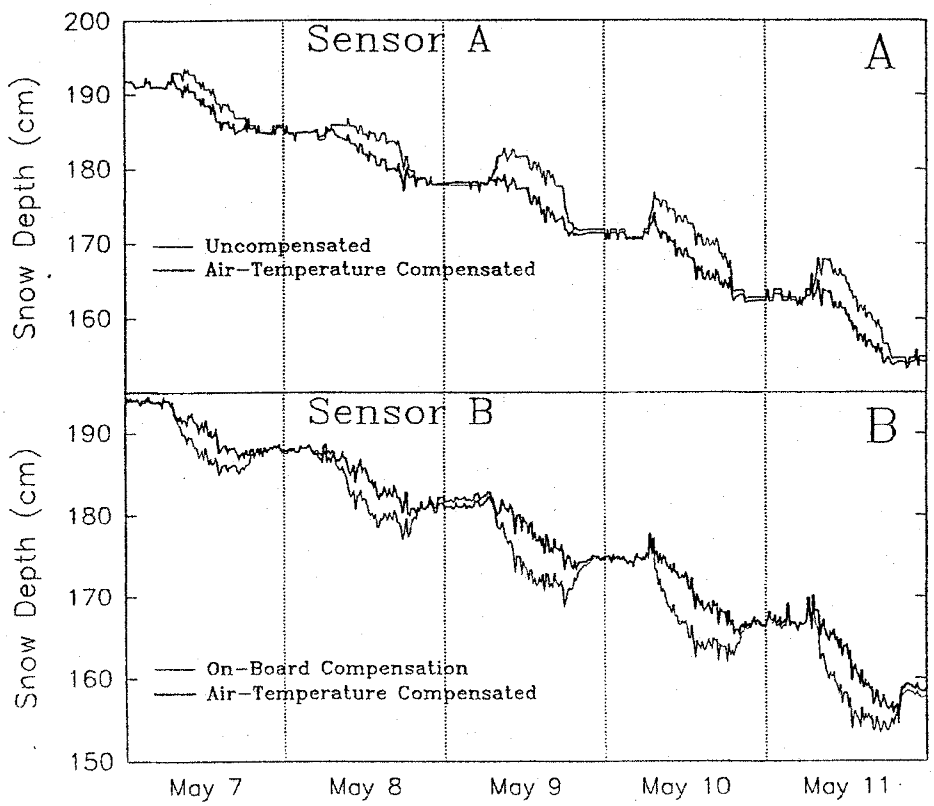

Figure 3. Sensor A and B depth fluctuations due to temperature variations, before and after temperature-correcting algorithms. Sensor A has no on-board compensation, Sensor B has temperature compensation.

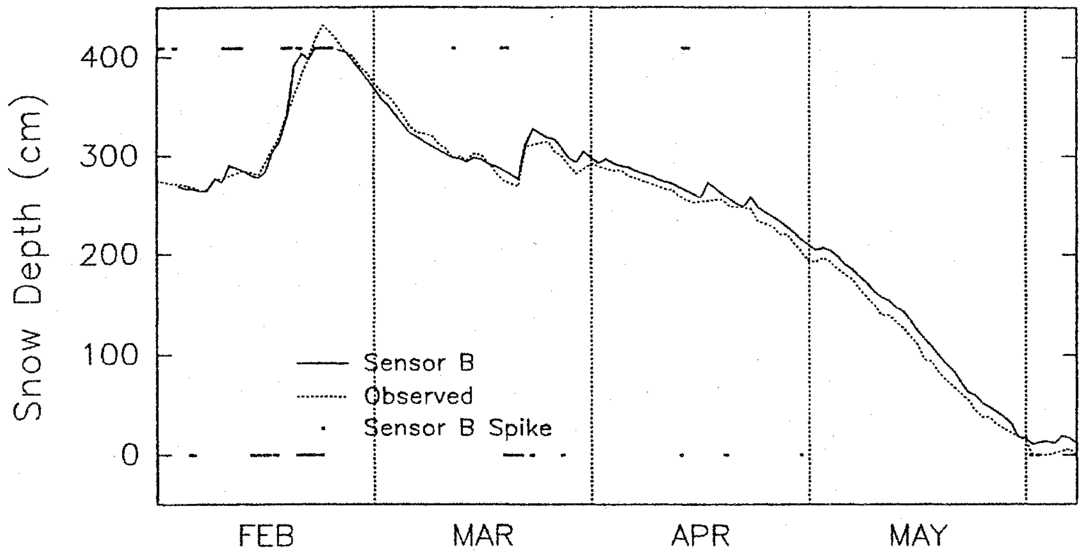

Figure 4. Seasonal tracking of snow depth by Sensor B compared to manual observations of snow depth at the Central Sierra Snow Laboratory, Soda Springs, California. Manual observations were taken daily at 0800.

squares decreased to 42%. We conclude that these corrections both reduce variation and better represent the melting and freezing processes that cause decreases in snowpack depth during ablation periods.

SENSOR BEHAVIOR ISSUES

Seasonal tracking of the pack depth by Sensor B is displayed in Figure 4. The data and visual observations match well throughout the four-month period. There is, however, an offset of approximately 10 cm, appearing in mid-March, that remains quite constant during the rest of the ablation period. Even though the sensor's target area and the master snow stake are only three meters apart, we suspect that differential accumulation and/or ablation caused the offset. Snow deposition and ablation are characterized by spacial variability.

The spikes displayed in the sensor data in Figure 4 reflect voltages at the extremes of the sensor's output range. The spikes have not been attributed to any meteorological effect, and the sensor malfunctions disappeared after short intervals. No mechanical or electrical explanation for this aberrant behavior was identified. We did not detect this problem with Sensor A, but that may be due to the processing that occurs in the DCR unit.

Mounting height for sensors is problematic. The closer the target is, the stronger the signal is, but the height should be above the maximum, long-term snow depth. Both of our sensors went out of range during a 10-day period at the end of February during which the snow depth peaked at 4.32 m.

We were concerned about interference by falling snow and the variation in the density of the target's surface, but we did not detect any problems in obtaining an accurate depth value either during periods of heavy snowfall or from any of a variety of warm or cold snow surfaces throughout the winter. The sensors tracked the snow depth well, during both periods of accumulation and ablation.

CONCLUSIONS AND RECOMMENDATIONS

The inherent errors associated with ultrasonic distance measurements, namely variations in air temperature, can be overcome with simple temperature-compensating algorithms. If an internally temperature-compensated sensor is employed, and that sensor's temperature differs from the temperature of the air in the sound's path, then an independent air temperature measurement is advised. By tightly enclosing both units in PVC pipe for weather protection and security, we introduced additional opportunity for Sensor B to read false air temperatures. It may be prudent to monitor air temperature inside any shelter that houses a temperature-compensating ultrasonic sensor. The simplest installation would entail a non-compensating ultrasonic sensor and an independent air temperature sensor. If only a few data points per day are required, making ultrasonic snow depth measurements between midnight and sunrise, when temperature gradients are low or absent, may be an easy alternative to subsequent data manipulation.

Though the temperature-compensating algorithms do not remove all the fluctuations from the depth data, we believe ultrasonics to be an excellent instrument for monitoring absolute depths of, or changes in, early-winter, mid-winter, and spring-time snowpacks. If sample times are standardized, even the raw data from an uncompensated sensor can give a reliable, seasonal picture of snow accumulation and ablation.

*no implied endorsement