AN EVALUATION OF THE ACOUSTIC SNOW DEPTH SENSOR IN A DEEP SIERRA NEVADA SNOWPACK

By

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INTRODUCTION

Information on snow depth has a wide variety of uses in the Sierra Nevada, ranging from forecasting water supply to planning snow clearing of highways and railways on high mountain passes. Currently, the usefulness of this data is severely limited because the information is collected manually only once per month.

California's network of 110 automatic snow sensors report snow water equivalent (SWE) several times each day, but they are not yet equipped to report snow depth. Equipping some data collection sites with a reliable snow depth sensor would greatly improve the utility of the snow information. Current uses of the data, like estimating the average density of the snowpacks, could be tracked more carefully, allowing better modeling of runoff. New uses, like estimating the hazard of backcountry avalanches from real-time data on snow depth, could begin. Other uses, like planning removal of snow from highways and railways, would greatly benefit from more timely information. Combining information on real-time snow depth with already available SWE, precipitation, and air temperature would allow much better tracking of rain-on-snow events, critically important during floods. Finally, data on snow depth could be used to improve quality control of automatically reported SWE, and possibly reduce the need for frequent trips to remote wilderness locations to collect ground-truth measurements. Clearly there is a need for a simple remote system for measuring snow depth where manual measurements are not available and where more frequent measurements are needed to properly manage water and other resources.

During the past several years a method for measuring snow depth using ultrasonic ranging devices has been under development. One version of an acoustic sensor has been tested in the shallow snowpacks of Canada (Goodison et al., 1984, 1988) and was found to give satisfactory performance when properly sited. At the USDA Forest Service's Central Sierra Snow Laboratory (CSSL), an acoustic sensor manufactured by Handar (Handar, 1986) was in operation during the 1987-88 winter. This paper evaluates the performance of that sensor in a deep Sierra Nevada snowpack during the 1987-88 winter.

SYSTEM CHARACTERISTICS

The acoustic sensor being tested at the CSSL is the Handar Model 445A non-contacting distance measuring sensor. It consists of a bell-shaped transceiver module that is mounted on a long horizontal arm directly above the target area. Mounting height depends on the maximum snow depth that is expected to occur at the measurement site but must be within a measurement range of 122 cm to 762 cm. A data collection platform (DCP), which includes a GOES satellite telemetry system, controls the operation of the sensor. When a pre-programmed query command is initiated by the DCP, the 445A sends a 5 second long series of 32 ultrasonic pulses, toward the snow surface, at a wavelength of 23 KHz. The mean and variance of the time difference between the series of pulses are calculated. A snow quality flag, scaled by the variance for each series of pulses, is added to the data set to determine the probability of error of the signal (0 = good, 9 = invalid). In the DCP, travel time is converted to the height of the sensor above the snow surface. This output is converted to snow depth by subtracting the sensed height above the snow surface from a known calibration height above the soil surface. The transceiver observes a 30-degree circular area of snow surface and has a measurement accuracy of +/-0.1% of the measured range. The DCP is programmed to measure snow depth in increments of no less than 3 cm (+/-3.0 cm of actual depth). Sensed snow depth is corrected electronically for changes in the velocity of sound associated with air temperature. At the CSSL, the system is currently being queried on an hourly basis. Information from the DCP is sent via the GOES satellite to the ground receiver station on top of the Resources Building in downtown Sacramento. The data is checked for errors electronically and archived by the California State Department of Water Resources.

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SITE AND METHODS

The CSSL is located west of the Sierra Nevada crest near Donner Summit at 2125 m elevation. Average seasonal snowfall is 1020 cm and an average peak depth of 305 cm is reached by mid-March. From 1977 to 1989, peak snow depth has varied between 90 and 480 cm.

The acoustic sensor was installed at the CSSL in November 1987. The transceiver module was mounted on a 3-m long boom 6.2 m above the ground surface directly over a 4-pan snow pressure pillow. This provided an excellent reflecting surface and coincident snow water equivalent measurements. The boom was supported by a cable to eliminate vertical movement during windy periods. Measurements of observed snow depth were obtained from a graduated tube 7.5 m from the target area. Snow depth, when measured by a graduated probe, is about 1.5 cm greater at the acoustic sensor site.

To evaluate sensor performance, observed snow depth and sensed snow depth at 8 A.M. were compared by simple linear regression analysis. During periods of no precipitation sensor data were analyzed for variation in sensed snow depth associated with fluctuation in air temperature. Although the Handar measurement system electronically compensates for variations in the velocity of sound associated with the temperature of the air mass, a cyclic variation of sensed snow depth prompted further analysis. Since the velocity of sound varies with air temperature, several days' worth of data were analyzed to determine what effect air temperature had on sensed snow depth and to see if variation in snow depth associated with changing air temperature could be reduced.

RESULTS AND DISCUSSION

Correlation between 75 readings of observed snow depth and sensed snow depth at 8 A.M. was high (r = 0.99), with a standard error of estimate of 3.6 cm (Figure 1). Snow depth during the test period reached 190 cm, and surface snow densities (top 10 cm) ranged from 80 kg/m^3 to 400 kg/m^3. Surface melt-freeze crusts reached a thickness of 40 cm. In most cases the acoustic sensor slightly overmeasured, with variations ranging from 0.2 cm to 9.9 cm. The greatest variations, however, occurred when the acoustic sensor undermeasured, with differences as high as 13 cm occurring throughout the range of snow depths. Measured snow depth in the acoustic sensor target area is greater than at the ground truth site and accounts for some of the measured variation. An additional source of measurement error may be a less well-defined snow-reflecting surface which can develop between storms resulting in an uneven, cup-like, surface in the target area. The ultrasonic pulse may not always reflect directly off the highest portion of the cupped surface, thereby creating positive or negative incremental hourly fluctuations.

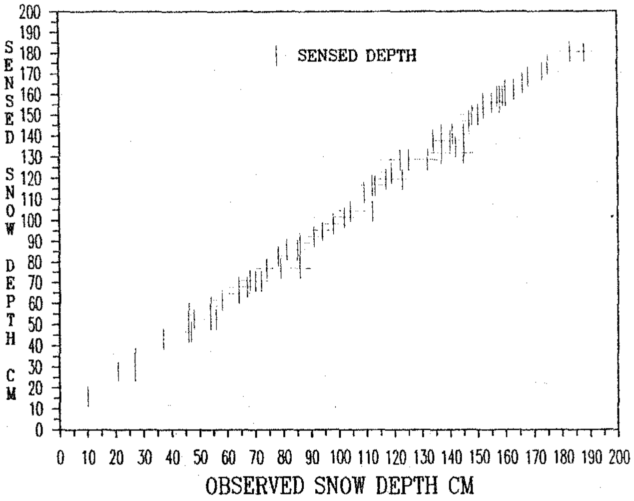
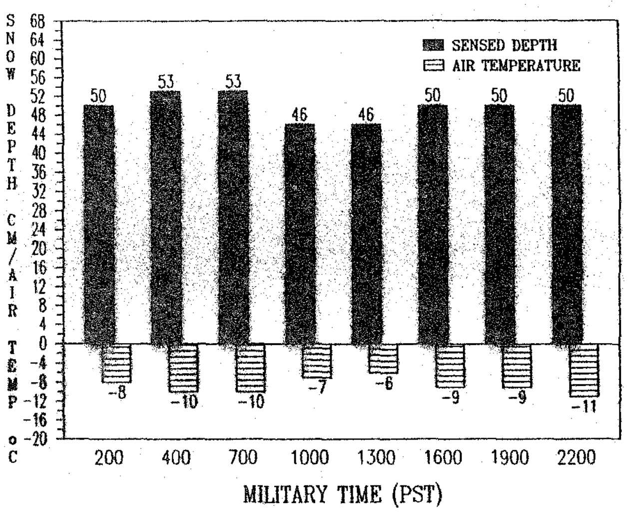


Figure 1. Correlation between sensed and observed snow depth at 8 A.M. was 0.99.

During 24 hour periods when there was no precipitation, snow depth from the acoustic sensor varied inversely with changes in air temperature. Snow depth varied to a lesser degree during small fluctuations in air temperature and vice versa. A variation of less than 5°C corresponded to a depth change of 7 cm or less and was very close to being within the design measurement resolution of +/- 3 cm (Figure 2). When temperature variation approached 16°C, however, snow depth fluctuation was almost 18 cm (Figure 3). This is well outside of the +/-3 cm measurement resolution. Although Handar states that its electronics package compensates for changes in the velocity of sound associated with variations in air temperature, it appears that there is still a problem related to air temperature. The air temperature thermistor located in the transceiver module within the inverted bell-shaped cone, may be subject to solar heating without the benefit of proper ventilation and may heat to beyond actual air temperature. Correcting for the velocity of sound using temperature data from the thermistor mounted in the sensor head may cause an exaggerated cyclic depth verses air temperature relationship. This would occur during the hottest part of the day.



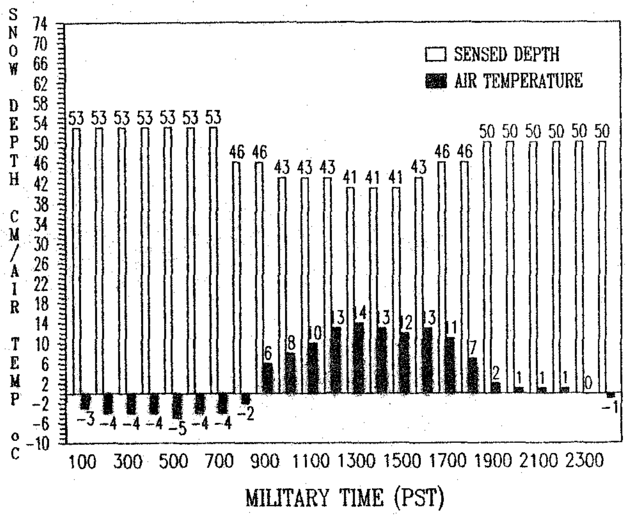


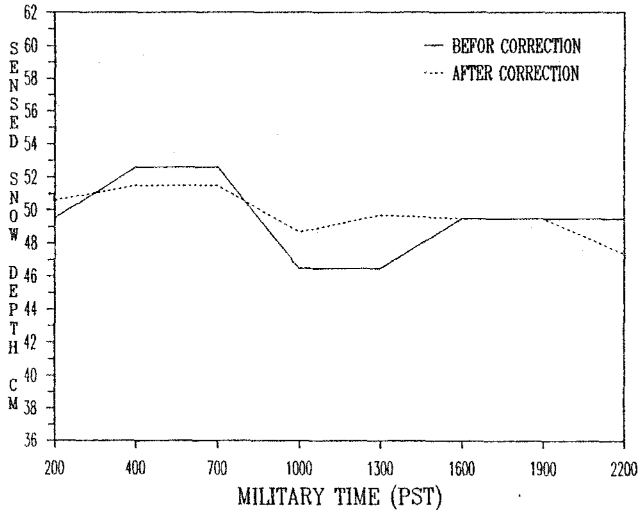
Figure 2. There was a low degree of sensed snow depth variation when diurnal air temperature fluctuations were small.

Figure 3. There was a high degree of sensed snow depth variation when diurnal air temperature fluctuations were large.

To test this hypothesis, data on sensed snow depth were corrected for changes in sound velocity associated with air temperature just as if there were no internal correction applied (Figures 4 and 5). This shift is linear (List, 1951), and a correction can be easily calculated for each degree of temperature change. An attempt was made to smooth this variation by correcting sensed snow depth for the velocity of sound at the average 24 hour temperature, in °C, using the following equation.

$$D_c = S_h - \frac{(S_h - D_s) \times V_a}{V_m}$$

Where: D_c = Corrected snow depth in meters.
D_s = Sensed snow depth in meters.
S_h = Height of the sensor at calibration in meters.
V_m = Velocity of sound at measurement air temperature in meters/sec.
V_a = Velocity of sound at average air temperature in meters/sec.



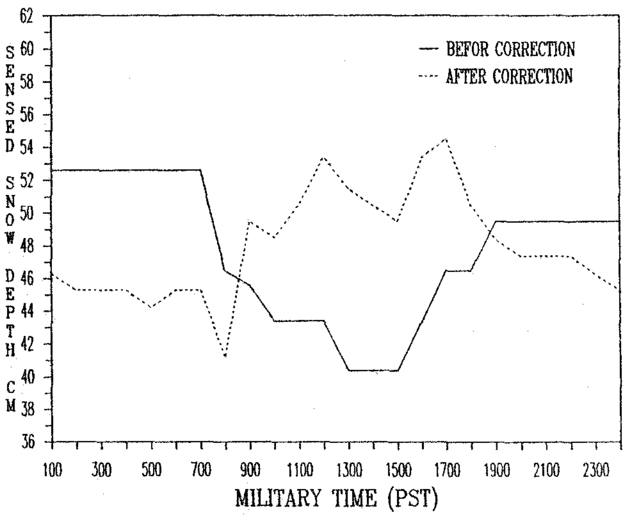


Figure 4. Corrected snow depth followed the same pattern as sensed snow depth when air temperature remained at below zero.

Figure 5. Corrected snow depth was inverse of sensed snow depth when air temperature cycled above and below zero.

Snow depth fluctuation was reduced significantly on December 12, 1987 when air temperature remained at below 0^{o} over the 24 hour period. The variation, however, could not be totally eliminated and the corrected depth followed the same pattern as the sensed depth (Figure 4). When snow depth was corrected for a cycle of temperatures above and below 0^{o} on March 24, 1988, the corrected depth followed a pattern inverse of the sensed depth and the fluctuation could not be reduced, in fact, it actually increased (Figure 5). These results lead me to believe that the Handar thermistor exaggerates maximum air temperature and that by using this data, the velocity of sound is overcompensated for due to thermistor overheating in the transceiver head.

CONCLUSION

The acoustic snow depth sensor showed a high correlation with ground truth at 8 A.M. (r = 0.99) throughout the 1987-88 winter season. There were very few system malfunctions and the data were seldom unusable. The ultrasonic depth measurement package does have a temperature problem, however. Although variations in the velocity of sound associated with changes in the temperature of the air mass are compensated for electronically, the thermistor located in the transceiver module appears to overheat. Overheating gives rise to a large hourly fluctuation in snow depth during periods without precipitation, with the highest discrepancy occurring in the afternoon when the range between night and daytime air temperature is the greatest. The variations associated with temperature were not constant and increased as the difference between daily maximum and minimum air temperature increased. With a measurement resolution of +/- 3 cm, snow depth cannot be measured with a high degree of accuracy. With the applications this sensor may be intended for, however, its current level of accuracy will suffice. When used in combination with other sensors, it can provide important information on snow depth for better modeling of runoff and during rain-on-snow events that can cause low elevation floods.

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