Comparison of Thermistor Sensors to Bandgap-Based Digital Sensors for Ground Temperature Measurements

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INTRODUCTION

In cold regions, ground temperature measurements are essential for engineering design and monitoring of capital projects throughout their life. Ground temperatures indicate the presence of permafrost and the depth of the seasonal active layer in permafrost and non-permafrost locations. Extrapolation of ground temperature data from one area to another is not advisable due to variations in local air temperatures, snow cover, vegetation, drainage, topography, and soil properties (Smith, 1996). Actual site measurements of ground temperatures are essential to determine the parameters for engineering design of foundations and buried utilities. Monitoring of ground temperatures once a project is constructed is advisable to determine if any changes occur to the thermal regime over the project's life. Monitoring also allows early detection of any changes that occur outside of the design parameters so that retrofits can be installed to salvage the project before early failure.

The thermistor has become the standard temperature sensor due to its rugged and simple construction, reliability, and accuracy (Miller, 1985). Thermistors are analog resistors that exhibit a repeatable change in resistance with temperature. The characteristic change in resistance of a thermistor can be either directly proportional or inversely proportional to a change in temperature. They are predominantly read in the field with a sensitive ohm meter and the resistances are recorded by hand.

Recently, the introduction of bandgap-based digital temperature sensors have simplified the acquisition of ground temperature measurements. The use of microprocessors to acquire and store the data from the sensors reduces the chance of human induced error during data acquisition. The potential for inexpensive and energy efficient digital data loggers that this technology facilitates also allows for long term measurements in remote locations.

The objective of this paper is to provide information on thermistor and bandgap-based temperature sensors and compares the two technologies for use in ground temperature acquisition.

BACKGROUND INFORMATION

Documented interest in ground temperatures has been around since 1789 when a Dr. Williams recorded soil temperatures in pastured and wooded areas in Vermont (Miller, 1985). In cold regions, the depth of the seasonal active layer (which is the depth where the ground temperatures seasonally change from being above to below freezing) is important for foundation and buried utility design (Andersland and Ladanyi, 1994).

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Ground temperatures also indicate the presence of permafrost, which is defined as, "the condition in which any material stays below 0° C for two or more years" (Smith 1996). The temperature of the permafrost is an important parameter in engineering design. Most ground temperatures in permafrost are measured as a one dimensional vertical array and the temperatures are plotted as a function of depth. If the ground temperatures are constantly measured over a full year, encompassing the freezing and thawing seasons, a "trumpet" curve can be plotted that shows the change in the temperature amplitude as a function of depth. Figure 1 is a schematic of a typical "trumpet" curve.

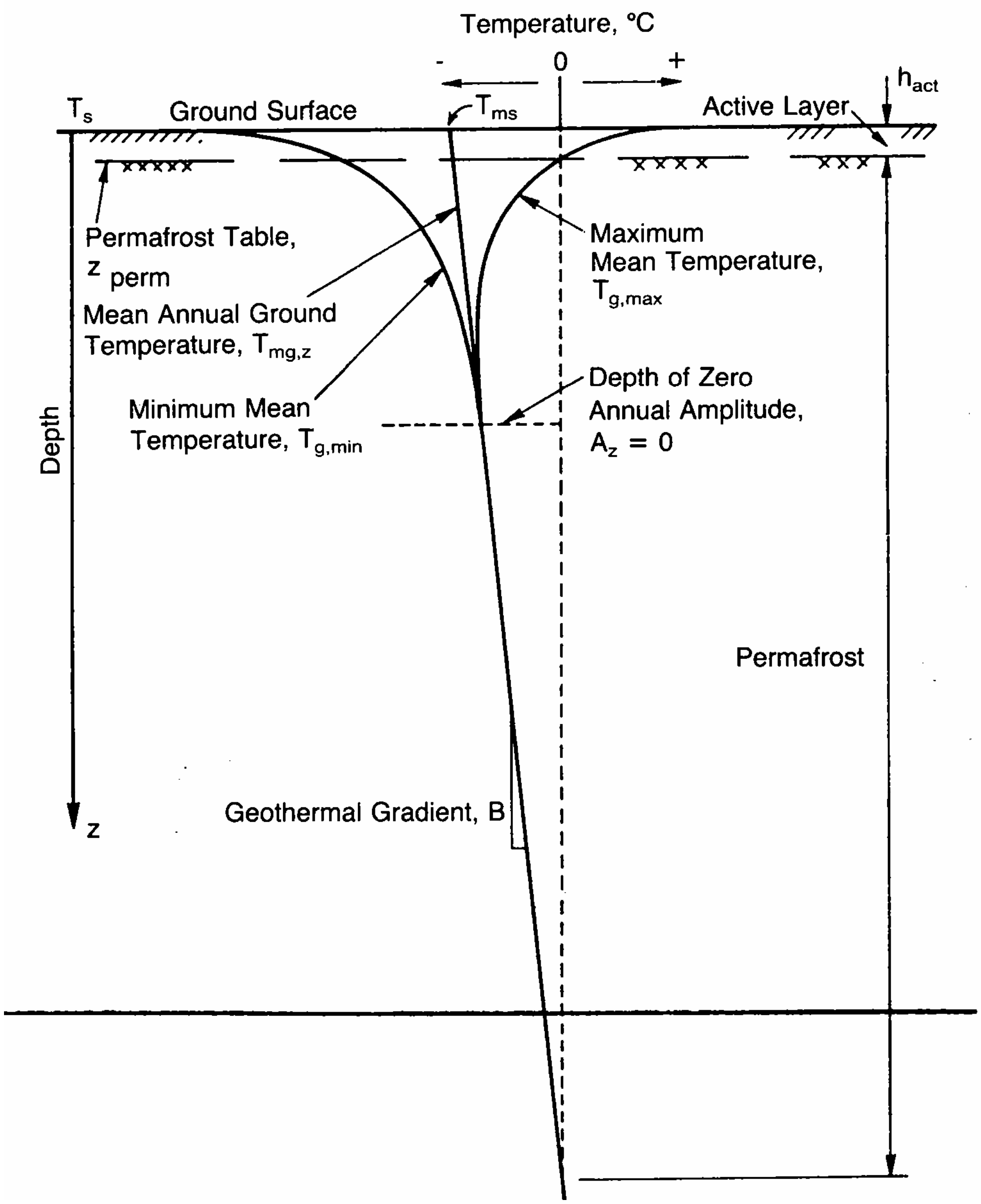

Figure 1: Schematic Ground Temperature "Trumpet" Curve (Smith 1996)

GROUND TEMPERATURE MEASUREMENTS

Thermistor sensors

Ground temperatures have been measured with thermometers, frost tubes, and thermocouples; however, the most common sensor currently in use for measuring ground temperatures is the thermistor (Osterkamp, 1984). Thermistors are a thermally sensitive resistor and can be manufactured with a negative temperature coefficient of resistance (NTC) or with a positive temperature coefficient (PTC). The most common type used for ground temperature measurements is the NTC thermistor. The advantages of thermistors include low cost, a high degree of sensitivity, low excitation power, and ruggedness. The disadvantages are a rather limited temperature range, nonlinearity of the correlation between resistance and temperature, and thermometric drift of the resistance to temperature correlation over time (Zurbuchen, 2000).

Thermistor cable arrays that are used for one dimensional vertical ground temperature measurements are manufactured using a multi-conductor cable with thermistor sensors installed at intervals. Each sensor is isolated in a dedicated circuit of two wires, completing a closed loop. A multi-pin connector is then installed at the end of the cable that can be connected to a switchbox. The individual circuits are identified with numbers that correspond to the numbering on the switchbox. The resistance across each thermistor within the circuit is measured with a sensitive ohm meter. For accuracies of ± 0.1° C, which is within the tolerance for most engineering work, the lead wire resistance is not significant for cables less than a few hundred meters in length (Miller, 1985). Figure 2 shows a typical thermistor cable, switchbox, and ohm meter setup.

Figure 2: Thermistor Cable Array Setup

After manufacture, the thermistor sensors are calibrated by placing the entire cable in a controlled ice bath and the resistances are recorded to correspond with a temperature of 0° C. The resistance is converted to temperature through the Steinhart and Hart equation:

$$\frac{1}{T} = a + b(\ln R) + c(\ln R)^3$$

Where:

T = Temperature (Kelvin)
R = Resistance (Ohms)
a, b, and c = Constants provided by thermistor manufacturer

Thermistor cable arrays are usually placed in a conduit, such as poly-vinyl chloride (PVC) pipe which has been installed in a test boring prior to backfilling. The conduit allows the cable to be installed temporarily and reused at different locations. After placement in the conduit, the thermistor sensors are allowed to come to equilibrium with the adjacent ground temperature. The resistances of the individual sensors are then measured with a sensitive ohm meter and recorded by hand in most cases. The resistances vary continuously (due to noise and self-heating of the sensors) and the technician must determine the most prevalent reading. The raw data is then usually entered into a spreadsheet that converts the resistance to temperature and adjusts the individual sensors to the ice-bath calibration.

Multi-channel data loggers are available to record the resistances of the thermistor sensors over time; however, they are expensive and require relatively large power supplies. The data loggers need to be programmed for specific applications and require training to use. Most of the engineering projects in Alaska that require ground temperature measurements are located off of the road system; a considerable distance from the main office of most companies. Since the measurements are recorded two or more weeks after drilling to allow the disturbance from the drilling operation to subside, it is desirable to have a local resident record the measurements and then ship the equipment back to the office. Usually, only one set of readings are recorded for each conduit.

Thermistor cable arrays are subject to damage at the thermistor sensor locations and the multi-pin connector. Since the cable contains multiple wires, it is stiff and heavy. The thermistors themselves are subject to damage during fabrication from overheating while soldering. The written data is subject to error by transposition during the acquisition and post-processing phases. Collecting the data can be time consuming and onerous when the field conditions are severe. Post-processing the data is also subject to error and takes additional time. For these reasons, the development of a simpler system to obtain ground temperature measurements was desired.

<u>Bandgap-based digital sensors</u>

Bandgap-based digital temperature sensors are silicon semi-conductors that rely on the characteristic variation in energy states between electrons occupying the top of the valence band and the bottom of the conduction band as the temperature changes. Sensor circuits based on this technology can be matched with a microcontroller that activates the circuit, performs analog to digital conversion, stores the result in memory, and receives and transmits data digitally. Digital-output temperature sensors are therefore particularly useful when interfacing with other microprocessor-based devices such as a PC or data logger (Smith, 2004). Modern manufacturing methods enable these functions to be combined into a single digital temperature sensor chip or integrated circuit (IC). These sensors are used in the computer industry to provide temperature feedback in heating and cooling circuits.

For ground temperature measurements, the sensors are installed on a cable array in similar fashion to thermistors except that the sensors are installed on only enough wires to facilitate a given communication protocol, typically one, two, or three wires regardless of the total number of sensors. This makes the cable much more flexible and lighter, which extends its life. The communication protocol allows sharing of information such as the sensor number, location, and status, as well as the current temperature. The microprocessor records this information and adjusts for the ice-bath calibration. The output is given in real temperature. The technician plugs the microprocessor into the cable and launches an algorithm which records and stores the data automatically; therefore, any potential error from transposing numbers while writing down the data by hand is avoided. The entire process takes only a few seconds.

BeadedStream©, based in Anchorage, Alaska, manufactures temperature cable arrays that utilize bandgap-based digital temperature sensors. They have also developed software designed to communicate with sensors of this type and acquire the data using a small handheld computer. The handheld computer is similar to many personal digital assistants (PDA's); however, it is robust and made for rough use in the field. Figure 3 shows the PDA and cable installed in a test boring.

Figure 3: BeadedStream© PDA and Bandgap-Based Digital Temperature Cable

Time constant data

The data acquisition program developed by BeadedStream© allows for successive temperature readings over time so that a time constant for the sensors to come to thermal equilibrium can be established. A time constant is obtainable using thermistors; however, either a data logger would need to be installed or the readings would have to be taken on a regular basis manually, which would be onerous. Using the BeadedStream© handheld computer, the program is launched and the technician can leave the site for the duration that the program is set to record for. The digital data is then downloaded directly into a spreadsheet to develop a time constant curve. Figures 4 and 5 show the time constants for selected sensors from bandgap-based digital cables installed in test borings in Nome, Alaska on March 9, 2007.

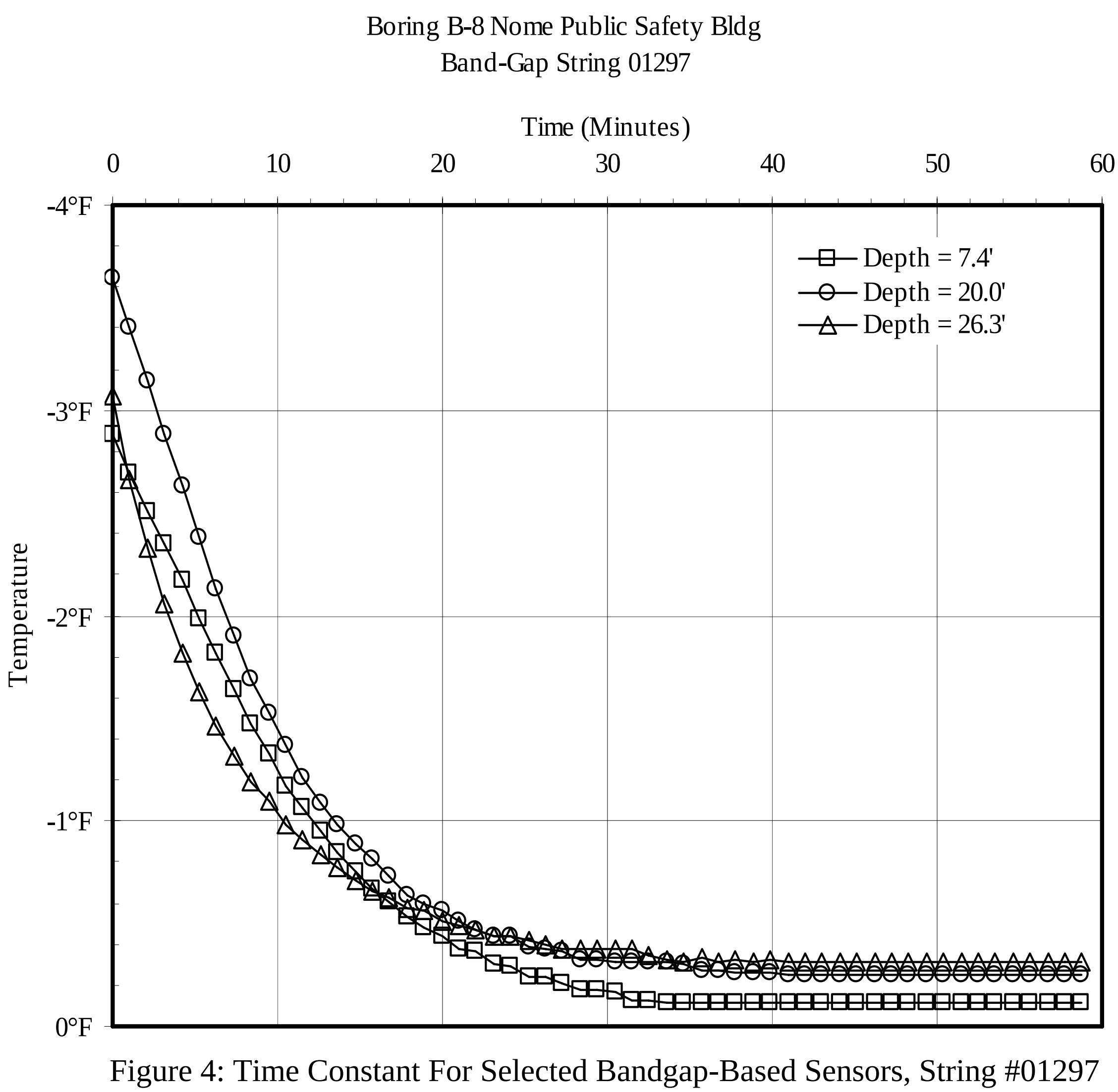

Figure 4: Time Constant For Selected Bandgap-Based Sensors, String #01297

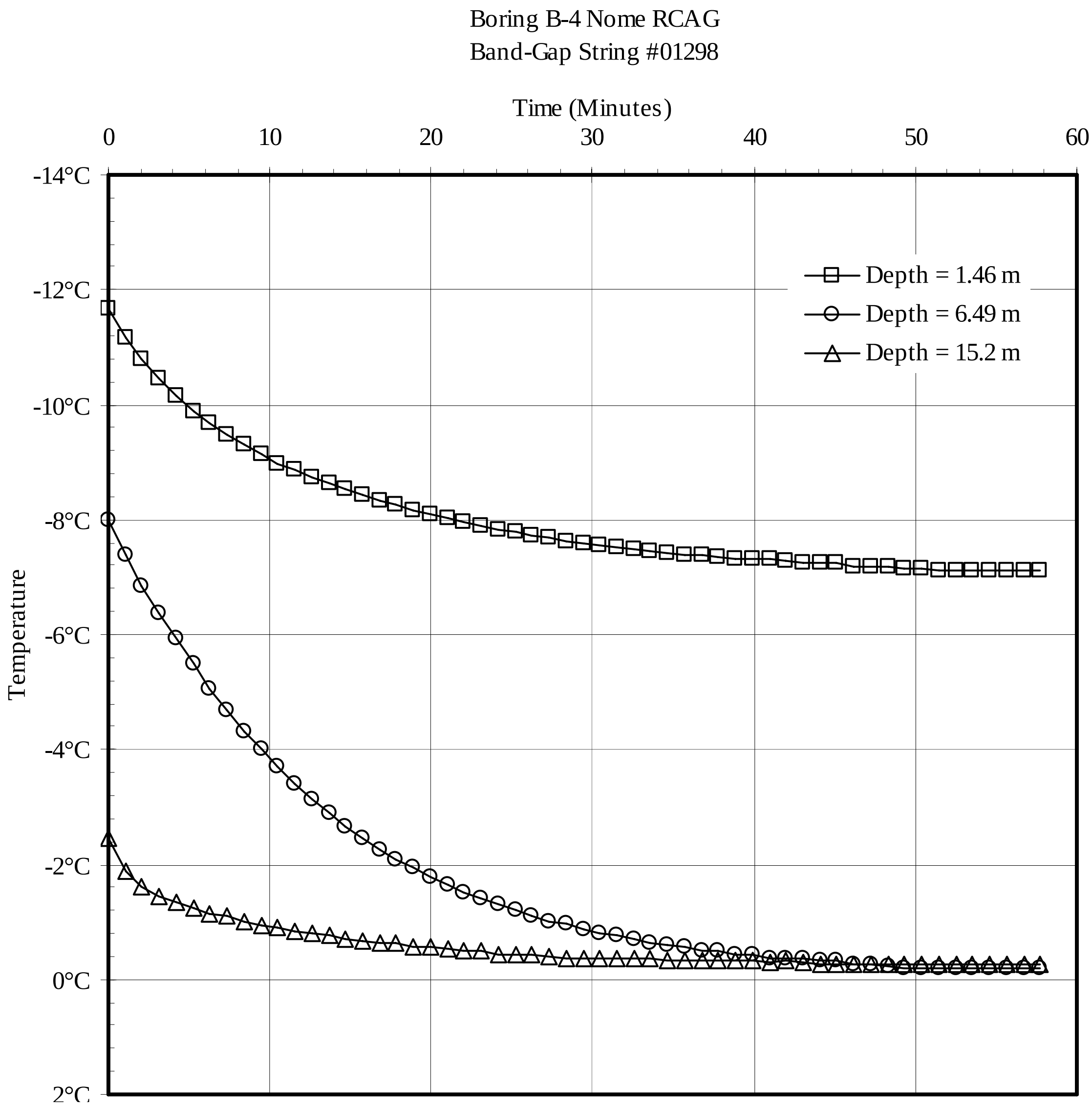

Figure 5: Time Constant For Selected Bandgap-Based Sensors, String #01298

The time constant data presented in Figures 4 and 5 indicates that the sensors reached thermal equilibrium approximately 40 minutes after being installed in the conduit. This information is important to determine the amount of time to let the cables sit before obtaining ground temperature readings.

Ground temperature comparisons

To compare ground temperature measurements between thermistors and bandgap-based digital temperature sensors, separate cable arrays manufactured with each sensor were installed in the same conduit concurrently in Nome, Alaska on March 9, 2007. The cables were allowed to sit in the conduit for more than 1 hour to reach thermal equilibrium. Figure 6 depicts one of the installations containing both cables.

Figure 6: Thermistor and Bandgap-Based Digital Cables Installed in Nome Test Boring

The thermistor sensors are YSI 55034 Glass Encapsulated (GEM) thermistors, manufactured by YSI Temperature, a division of Yellow Springs, Inc. According to YSI, “the specially formulated glass material has improved stability compared to epoxy or plastic encapsulated thermistors. They are ideal for applications requiring high stability up to 200°C, or in high-moisture environments” (YSI, 2007). The specifications for YSI 55034 thermistors are shown in Table 1.

Table 1: YSI 55034 Thermistor Specifications

Interchangeability Tolerance (0° C to 70° C)	Best Working Temperature	Thermometric Drift (10 Months at 25° C)
± 0.1° C	-80° C to +125° C	< 0.01° C

The interchangeability tolerance refers to how accurately thermistors track a nominal resistance curve. In the case of the YSI 55034 thermistor, the tolerance is within ±0.1° C of the nominal value through all portions of the interchangeable range. This term is sometimes confused with accuracy. The ±0.1° C value only refers to the nominal curve; absolute accuracy for the thermistor at a measured temperature is significantly better (YSI 2007).

The band-gap based digital sensors are manufactured by Dallas Semiconductor, a division of Maxim Integrated Products, Inc. based out of California. The actual part number and specifications are proprietary information to BeadedStream©.

The resistances of the thermistor sensors were measured with a Fluke Model 87 digital multi-meter with 4 ½ digit precision. The cable was connected to a switchbox that contained a rotary selector switch. After switching to a particular sensor, the readings were allowed to stabilize, and the resistance was recorded by hand. The handwritten data was entered into a spreadsheet that converted the resistance data to temperature using the preceding Steinhart and Hart equation. For the YSI 55034 sensors, the Steinhart and Hart constants are shown in Table 2. The temperature values were corrected for the ice-bath calibration in the spreadsheet.

Table 2: Steinhart and Hart Constants for YSI 55034 Thermistor Sensors

Constant	Value
a	0.00128444
b	0.00023626
c	0.000000092776

The temperature values of the bandgap-based digital sensors were measured with an Archer Field PC manufactured by Juniper Systems, Inc. The data acquisition software was developed by BeadedStream© and runs on the Windows Mobile 5.0 operating system. The temperature data was corrected for the ice-bath calibration within the data acquisition software. The data was transferred to a USB flash drive and then imported into a spreadsheet for analysis.

The corrected temperature data for both of the sensor types was plotted according to depth in a typical one dimensional ground temperature array. The sensors on each cable were not at equal spacing, so the data points were connected by straight lines to compare the values. The plotted ground temperatures are depicted in Figures 7 and 8 for the two test borings in Nome.

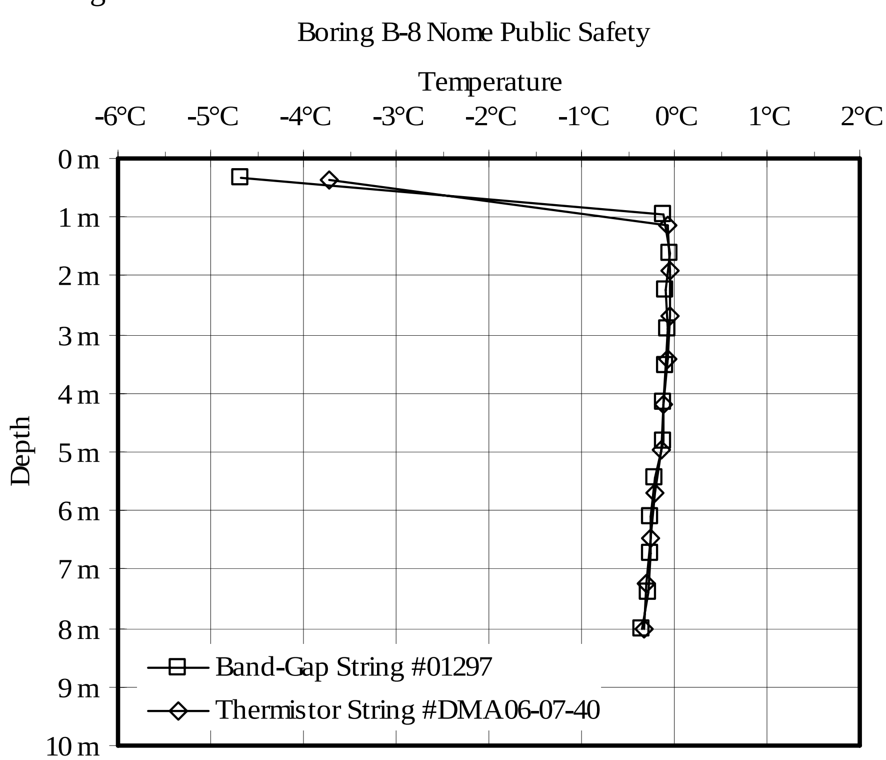

Figure 7: Ground Temperature Data – Boring B-8, Nome, Alaska

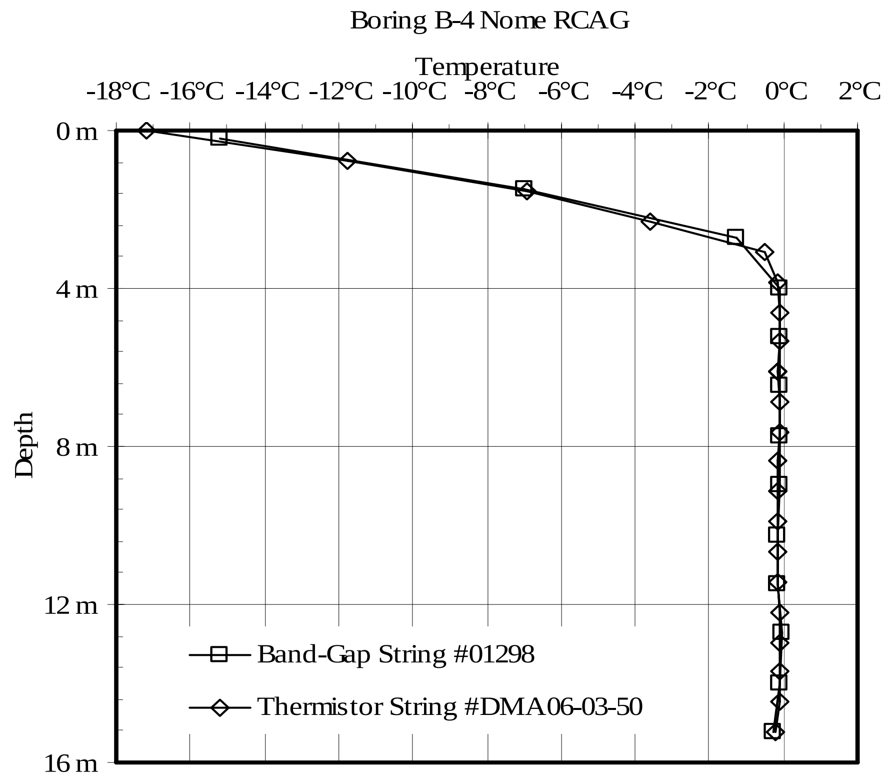

Figure 8: Ground Temperature Data – Boring B-4, Nome, Alaska

SUMMARY AND CONCLUSIONS

The ground temperature plots from both of the test borings in Nome show that the temperature curves for the thermistor and bandgap-based digital sensors fall almost on top of each other. At the very bottom of the test borings, where sensors from both cables were located, the temperature difference was 0.03° C in Boring B-8 at the Public Safety site and 0.02° C in Boring B-4 at the RCAG site. This discrepancy is well within the tolerances of the sensors themselves and are acceptable for engineering purposes.

Although thermistors have proven to be a reliable sensor for ground temperature measurements, the new band-gap based digital sensors provide possibilities to expand upon the data acquisition. These possibilities include simpler procedures for data acquisition, less potential for human induced error, and long term continuous measurements at remote locations.

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