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On the USCRN Temperature System

Kenneth Hubbard
University of Nebraska- Lincoln, khubbard1@unl.edu

X. Lin
University of Nebraska - Lincoln

C.B. Baker
National Climatic Data Center

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K. G. HUBBARD AND X. LIN

High Plains Regional Climate Center, School of Natural Resources, University of Nebraska at Lincoln, Lincoln, Nebraska

C. B. BAKER

National Climatic Data Center, Asheville, North Carolina

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ABSTRACT

In 2004 a new aspirated surface air temperature system was officially deployed nationally in the U.S. Climate Reference Network (USCRN) commissioned by the National Oceanic and Atmospheric Administration. The primary goal of the USCRN is to provide future long-term and high-quality homogeneous observations of surface air temperature and precipitation that can be coupled to past long-term observations for the detection and attribution of present and future climate change. In this paper two precision air temperature systems are included for evaluating the new USCRN air temperature system based on a 1-yr side-by-side field comparison. The measurement errors of the USCRN temperature sensor are systematically analyzed, and the components of error attributable to the datalogger, lead wires, fixed resistors, and the temperature coefficient of the resistors are presented. Although the current configuration is adequate, a more desirable configuration of USCRN temperature sensor coupled with the datalogger is proposed as a means of further reducing the uncertainty for the USCRN temperature measurement.

1. Introduction

A new program for national surface climate monitoring, the U.S. Climate Reference Network (USCRN), was started in 2001. The major goal of the USCRN is to provide long-term high quality climate observations, especially for the air temperature and precipitation over the next 50 to 100 yr. The USCRN program was officially commissioned by the Department of Commerce and the National Oceanic and Atmospheric Administration in 2004. Long-term climate monitoring with high quality observation is crucial to understanding issues of climate change and any impacts on the U.S. economy. It is well known that air temperature measurement systems contain two components: a temperature sensor and a temperature radiation shield. Both are critical for achieving a complete coupling between the sensor and the atmosphere, whereby an equilibrium temperature of atmosphere is inferred by the temperature of the sensor's body (Lin et al. 2001).

Corresponding author address: Kenneth G. Hubbard, High Plains Regional Climate Center, 244 L. W. Chase Hall, University of Nebraska at Lincoln, Lincoln, NE 68583-0728.
E-mail: khubbard1@unl.edu

Probably there is no single climate variable that has been studied more than surface air temperature. However, for the long-term historical surface temperature records, many scientists and climatologists have made tremendous efforts to adjust for the inhomogeneities of past and present measurements over the world (Peterson et al. 1998). A successful monitoring program must be able to evolve with changes in technology and funding such that there are minimal impacts on data quality and homogeneity of past, present, and future measurements (Karl et al. 1995). Therefore, the instruments or sensors selected for the new long-term regional and national climate monitoring system should, as much as possible, preclude the need for the future adjustments. For these reasons we considered it essential to conduct a site-by-site comparison between the USCRN air temperature sensor and other precision air temperature systems, to collect sufficient data for a field investigation of any differences that may have been introduced in this new USCRN air temperature system. On the other hand, the issue of whether or not the current design of the USCRN air temperature measurements is appropriate needs to be examined based on the accuracy requirement of the USCRN program.

TABLE 1. Characteristics of temperature sensors and shields used in this study.

Temperature systems		USCRN	RMY	PMT
Sensor	Manufacturer or vendor	Thermometrics Co.	R. M. Young Co.	Yankee Environ. Systems, Inc.
	Sensing element	Class A PRT	HY-CAL PRT	PRT
	Resistance at 0°C (ohms)	1000	1000	100
	Excitation source	1500 mV DC	2000 mV DC	0.4 mA AC
	Temperature range (°C)	+/−50	+/−50	+/−50
	Stated accuracy (°C)	+/−0.1 to 0.3	+/−0.1	+/−0.05
Shield	Electrical fan's power	12V DC	12V DC	12V DC
	Fan's flow rate (CFM)	82.4	15	25
	Outer diameter (mm)	89 mm	33 mm	60 mm
	75% ventilation rate (m s^{-1})	3.7	6.2	3.1
	Numbers of shielding walls	Triple	Double	Triple
	Air intake entrance	Double meshed	Open	Single meshed

In the USCRN, a platinum resistance thermometer (PRT) is housed in an aspirated radiation shield (model 076B motor aspirated temperature shield, Met One Instruments, Inc.). At each operating site, the USCRN employs three PRT temperature sensors to take redundant temperature observations for intercomparison and quality assurance. In this study, two comparative air temperature systems are included during our site-by-site comparison. One is an aspirated R. M. Young temperature sensor [model 43347 resistance thermometer detector (RTD) temperature probe and model 43408 aspirated shield, R.M. Young Co. (RMY)]. The second is a PMT-2005 Precision Meteorological Thermometer (PMT; Yankee Environmental Systems, Inc). The specifications of each temperature system, including both temperature sensor and corresponding radiation shield used, are listed in Table 1. The reason for selecting the RMY as a comparative temperature systems is that "this instrument (RMY) is widely used in meteorological studies, and has been subjected to extensive field tests that indicate, in typical monitoring situations, including maximum solar radiation, rapid nighttime cooling, precipitation, and variable wind conditions, that ambient temperature can be measured with an RMS error of less than 0.1°C. With like shields and sensors at two elevations, temperature difference can be measured to 0.05°C" (Stein et al. 2000). The PMT system is a stand-alone high-precision temperature measurement system that can provide measurements to an uncertainty of less than ±0.02°C solar radiation error. In addition, the electronics considerations in the PMT design are limited within ±0.01°C (Stein et al. 2000). Both comparative systems were calibrated [National Institute of Standards and Technology (NIST)-traceable] prior to field comparison (Table 1).

Unlike the traditional climate monitoring network several decades ago, the modern automatic climate networks usually take remote observations by using an on-site data acquisition system or datalogger to interrogate the individual sensors. At the USCRN site, a CR23X datalogger (Campbell Scientific, Inc.) was selected to interface with all sensors. The CR23X provides six methods for resistance temperature measurements with different bridge circuit configurations (Campbell Scientific, Inc. 2003). To make an appropriate resistance measurement with sufficient accuracy and sensitivity in the CR23X, it is critical to estimate the measurement error propagated by the given sensor, the interface between sensor and datalogger, and the datalogger.

The objectives of this note are to present site-by-site comparison results when comparing the USCRN air temperature with the RMY and PMT air temperature systems, schematically analyze measurement errors of the USCRN temperature sensor, and propose a more desirable configuration of USCRN temperature sensor as a means of further reducing the uncertainty for the USCRN temperature the measurement.

2. Field comparison

a. Instrument siting and data collection

The side-by-side comparison was conducted from November 2002 to November 2003 at the University of Nebraska's Horticulture Experimental Site (40°83'N, 96°67'W; elevation 383 m). The site was regularly maintained over a uniform ground surface. Our experiment consisted of one USCRN PRT sensor housed in the USCRN radiation shield, one RMY, and one PMT system, as well as one silicon pyranometer for global solar radiation measurements and one anemometer for ambient wind speed. The installation height of all temperature sensors, the pyranometer, and the ambient wind speed sensor was 1.5 m. The separation of comparative temperature sensors was 2.5 m, and they were located within a temperature sensor array zone (10 m). Both the USCRN PRT temperature sensor and RMY system were measured by using a CR7 measurement and control system (Campbell Scientific, Inc.). Data from the PMT system was collected using a personal computer through an RS232 protocol. In this study, data were collected continuously during the period November 2002 to November 2003, except for the month of April 2004, when site annual maintenance was performed. The data sampling rate was 5 s, and temperature signals were averaged over 1-min outputs. Hourly average for temperatures, solar radiation, and ambient wind speed were calculated from the 1-min data for this study. The available data for each month were taken after deleting all records wherein data from any one variable was missing (Table 2). During the approximately 1-yr period, observations of hourly ambient temperature, hourly solar radiation, and hourly ambient wind speed ranged from −23.1° to 38.4°C, 0 to 919 W m^{-2}, and 0 to 7.0 m s^{-1}, respectively.

b. Comparison results

Table 2 shows the overall monthly bias computed from differences between the USCRN and RMY and differences between the USCRN and the PMT. The occurrence of negative bias of the monthly average in June, July, and August suggests there was a warming bias for the RMY system during summertime in monthly average. For the PMT system, there were no obvious changes in monthly average during summertime in 2003. Compared to the RMY and PMT temperature systems, under a 95% confidence level the temperature difference ranges in monthly average in Table 2 were from −0.22° to +0.27°C and from −0.17° to +0.11°C. Regardless of whether the RMY or PMT is used as a reference, the USCRN air temperature sensor was able to meet the accuracy requirements (±0.1° to 0.3°C) proposed by the USCRN program in terms of monthly average. Although the monthly average differences or biases were a few hundredths of a degree Celsius, the obvious warming biases in the RMY system are clearly illustrated in Fig. 1. Increasing solar radiation produced a decreasing trend of temperature difference between the USCRN and the RMY irrespective of ambient wind speed (Fig. 1a). The magnitudes of temperature difference reached 0.2°C when the solar radiation was higher (e.g., solar radiation was greater than 400 W m^{-2}). When the same temperature differences were plotted against ambient wind speed, it turns out

TABLE 2. Observation data and monthly performance (AVE: monthly average; STD: monthly standard deviation) of USCRN sensor compared to the RMY and PMT systems.

Date	Hourly observations	USCRN-RMY (°C)		USCRN-PMT (°C)	
		Avg	Std dev	Avg	Std dev
Nov 2002	665	0.05	0.07	−0.04	0.04
Dec 2002	611	0.06	0.07	−0.04	0.05
Jan 2003	744	0.07	0.09	−0.02	0.04
Feb 2003	547	0.05	0.11	−0.04	0.04
Mar 2003	715	0.05	0.14	−0.04	0.04
May 2003	564	0.03	0.15	−0.04	0.04
Jun 2003	465	−0.01	0.16	0.02	0.15
Jul 2003	590	−0.05	0.16	0.00	0.08
Aug 2003	588	−0.05	0.13	−0.04	0.08
Sep 2003	678	0.01	0.17	−0.04	0.12
Oct 2003	584	0.01	0.11	−0.04	0.10
Nov 2003	636	0.07	0.10	−0.02	0.05
Bias range of monthly average @ 95% confidence level		[−0.22 to +0.27]		[−0.17 to +0.11]	

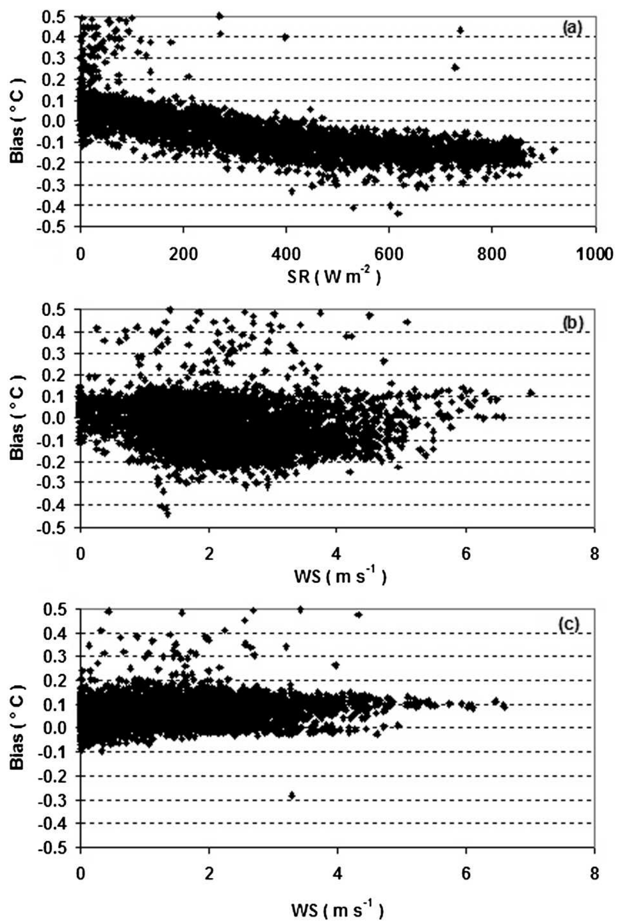

FIG. 1. Solar radiation (SR) and ambient wind speed (WS) effects on the bias (difference between the USCRN and the RMY): (a) solar radiation vs temperature bias, (b) ambient wind speed vs temperature bias during daytime, (c) the same as (b) but during nighttime.

that there were no obvious trends during either daytime or nighttime (Figs. 1b,c). Obviously, the nighttime USCRN temperature observations had smaller variations than observations during daytime. Figure 2 shows changes of temperature difference or bias between the USCRN and PMT during daytime and nighttime. Compared to Fig. 1a, there were no solar radiation effects on the temperature difference between the USCRN and PMT (Fig. 2a). For the ambient wind speed effects, the USCRN temperature sensor did not show obvious variations or trends (Figs. 2b,c).

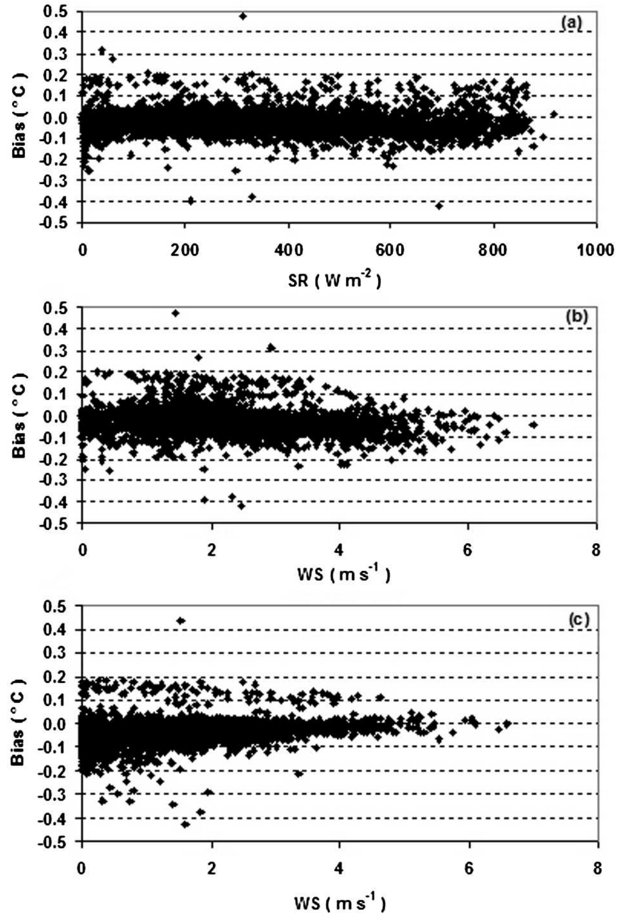

FIG. 2. As for Fig. 1, except the bias is the difference between the USCRN and the PMT.

3. Measurement errors and configurations of USCRN sensor

a. *Concepts of measurement errors*

There are a few measurement techniques available to the CR23X user for making resistance measurements: the ratiometric measurement method eliminates errors caused by the voltage reference; the self-calibration technique significantly improves measurement accuracy by compensating for signal conditioning drift and electrical component aging; and reversing the excitation polarity and input can eliminate the effects of external and internal offset voltage errors. Therefore, under the assumption of complete coupling between the USCRN temperature sensor and atmosphere, the measurement errors of USCRN temperature originate from the sensing element, analog signal conditioner, and the CR23X. These individual errors can be estimated from errors caused by the fixed resistor's tolerance (fixed resistor error), errors caused by the temperature coefficient of resistance (TCR) of the fixed resistor (TCR error), lead wire resistance (lead wire error), and uncertainty of resistance measurement by the CR23X (CR23X error). Both fixed resistor error and TCR error can be computed based on the specifications of the fixed resistor(s) and the signal conditioning circuitry. Note that the TCR is expressed as the change in resistance [in parts per million (ppm)] with each degree Celsius in temperature. This change is not linear with temperature, but it is reasonable to treat it as being linear over a limited range in the error analysis. Although the lead wire resistance is supposed to be compensated in most of resistance measurement methods in the CR23X datalogger, we demonstrate its existence due to possible difference of wire resistance in this note. The CR23X error refers to the resistance accuracy in the CR23X, which is specified to have ±0.015% of full-scale range (FSR) of the input voltage on which the measurement is made in the range 0° to 40°C and accuracy of ±0.02% of FSR elsewhere but still within −25° to 50°C. Therefore, in this note an accuracy of ±0.02% of FSR in the range −50° to −25°C is assumed for the CR23X datalogger, although the error might be underestimated. A root-sum-of-squares (RSS) of each error component was conducted for the total error of temperature measurement in the USCRN temperature sensor.

b. *Configurations of USCRN PRT sensor*

The selection of resistance temperature configuration must be based on the desired accuracy and data acquisition system to be used for the specific measurements. The USCRN air temperature requires an overall measurement accuracy of ±0.1° to 0.3°C; thus, this overall accuracy range should additively include any errors caused by the USCRN PRT sensor, the CR23X datalogger, and incomplete coupling between the atmosphere and air temperature radiation shield. Due to the PRT sensor's small resistance sensitivity (typically

0.385% or 0.39% per degree Celsius), three possible lead wire configurations can be selected for the USCRN air temperature measurement based on the CR23X datalogger (Fig. 3). Figure 3a is a three-wire half-bridge configuration that is currently used in the USCRN network. Figures 3b and 3c are four-wire half-bridge and six-wire full-bridge configurations. The lead wire resistance is compensated in all three configurations. For example, the lead wire resistance of RA and RB is cancelled out, and RC has no effect on the voltage measurement due to the large input impedance of the CR23X datalogger (lead wire resistance is only shown in Fig. 3a). The details of resistance measurement by the CR23X are listed in Table 3. The current configuration used in the USCRN requires fewer input channels compared to the other two. However, the performance of the percentage of FSR used, resolution, and current flow through the USCRN PRT sensor in these two configurations are better than the current configuration used in the USCRN (Table 3).

c. *Measurement errors*

For the current configuration used in the USCRN and two proposed configurations for the USCRN temperature sensor, the measurement errors of USCRN temperature for each configuration are shown in Fig. 4. The current configuration used in the USCRN demonstrated the total RSS temperature measurement errors in a range from 0.2° to 0.33°C, which is larger than the stated accuracy required by the USCRN program (see Table 1), irrespective of any errors caused from incomplete coupling between the temperature monitoring system and atmosphere. This total RSS error is not only due to the three-wire half-bridge configuration (Fig. 4a), but also the error caused by TCR of the fixed resistor is large. However, both four-wire half-bridge and six-wire full-bridge configurations are capable of considerably reducing the measurement errors caused by the CR23X datalogger (Figs. 4b and 4c). For the error caused by the fixed resistor's TCR, obviously the ±10 ppm $°C^{-1}$ TCR selected in current USCRN sensor is inappropriate (Fig. 4a). Therefore, the ±3 ppm $°C^{-1}$ TCR for the fixed resistor(s) is applied in both four-wire half-bridge and six-wire full-bridge configurations, shown in Figs. 4b and 4c. Note that both the four-wire half-bridge and six-wire full-bridge configurations also demonstrate relatively smaller errors in the lead wire error and in the fixed resistor's tolerance. From the view of total RSS error, the six-wire full-bridge configuration has the smallest errors, but it requires three fixed resistors in close proximity to the USCRN PRT sensing element. It is also clear that the four-wire half-bridge is

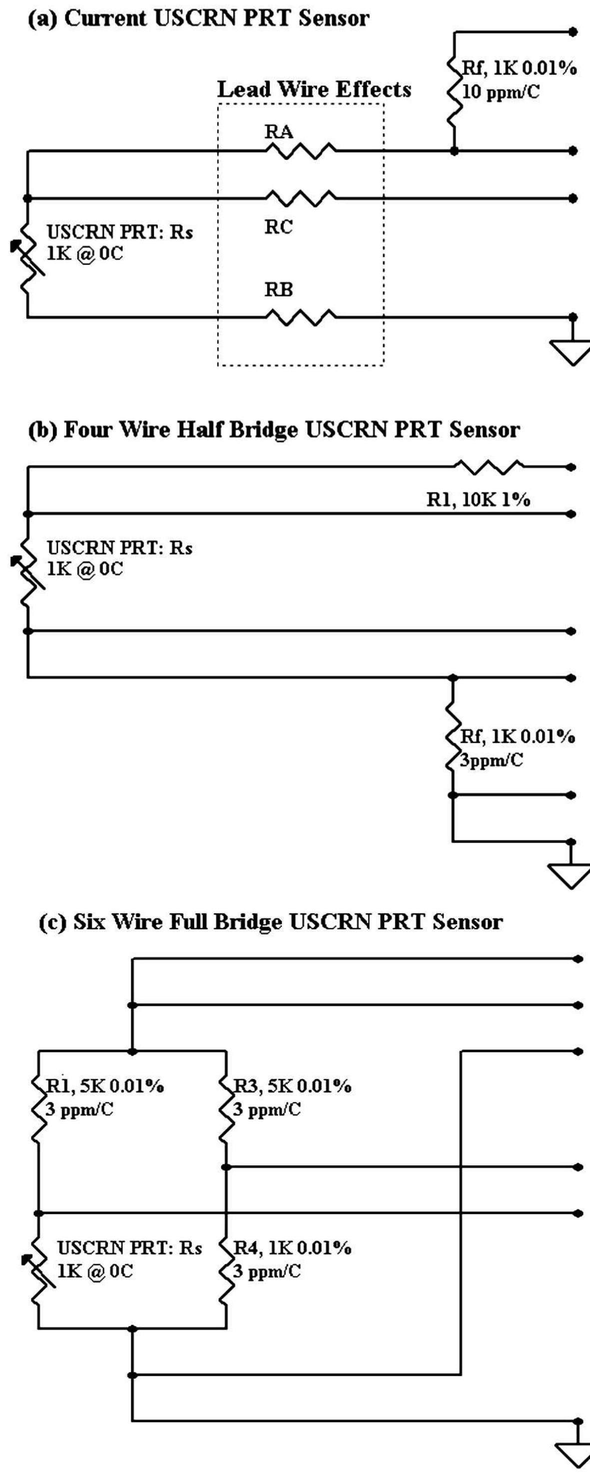

FIG. 3. Configurations of (a) current USCRN PRT, (b) proposed four-wire half bridge for USCRN PRT, and (c) proposed six-wire full bridge for USCRN PRT.

TABLE 3. Resistance measurements in the CR23X datalogger.

Configuration, instructions used	Excitation (mV)	FSR of input (mV)	Number of channel	Output (ratio)	Sensitivity (mV °C^{-1})	Percentage of FSR	Resolution (°C)	Current (mA)
3-wire half bridge, P7	1500	±1000	Two SE*	Rs/Rf	1.2 to 1.8	7	0.04	0.75
4-wire half bridge, P9	2000	±200	Two diff**	Rs/Rf	0.57 to 0.63	15	0.02	0.17
6-wire full bridge, P9	1750	±50	Two diff	R1/(R1 + Rs) −R4/(R3 + R4)	0.88 to 1.0	95	0.002	0.29

* SE refers to the single-ended input channel.
** Diff refers to the differential channel, and one diff is equal to two consecutive SE channels.

a better choice for accuracy where the USCRN PRT is separated from the fixed resistor(s).

4. Concluding discussion

Compared to the RMY and PMT temperature systems in the field, the USCRN PRT temperature sensor system is capable of reaching accuracies of ±0.2° to ±0.3°C at a 95% confidence level on a basis of monthly average if one of two comparative sensors, RMY and PMT, is used as an absolute reference. However, the warming bias was identified in the RMY system in this note due to the solar radiation influence. Note that the resistance measurement accuracy in the CR7 (±0.01% of FSR over −25° to 50°C) is almost double that in the CR23X (±0.02% of FSR over −25° to 50°C). Therefore, the field intercomparsion results in this note are representative of the USCRN temperature sensor performance and suggest that the USCRN temperature sensor system is free of both solar radiation and wind speed effects. It should be noted that the field intercomparison data collected in this study represent a 1-yr period, during which one cannot expect that extreme low or high temperature conditions will occur. However, the measurement errors under extreme conditions were schematically and electronically analyzed in our study.

Based on the evidence presented in this note, we recommend that the USCRN program move to one of two proposed configurations to make USCRN air temperature measurements. Although the input channels are doubled for these two configurations the measurement errors inherent in the temperature sensor and datalogger system are significantly decreased. For fixed resistor(s) employed in the USCRN sensor, ±0.01% tolerance is applicable, but the TCR of ±10 ppm °C^{-1} is not sufficient to provide accurate long-term temperature observations. The extreme high or low temperature ranges did not occur during the observations on which we report herein, but any component employed at the USCRN temperature system should consider its

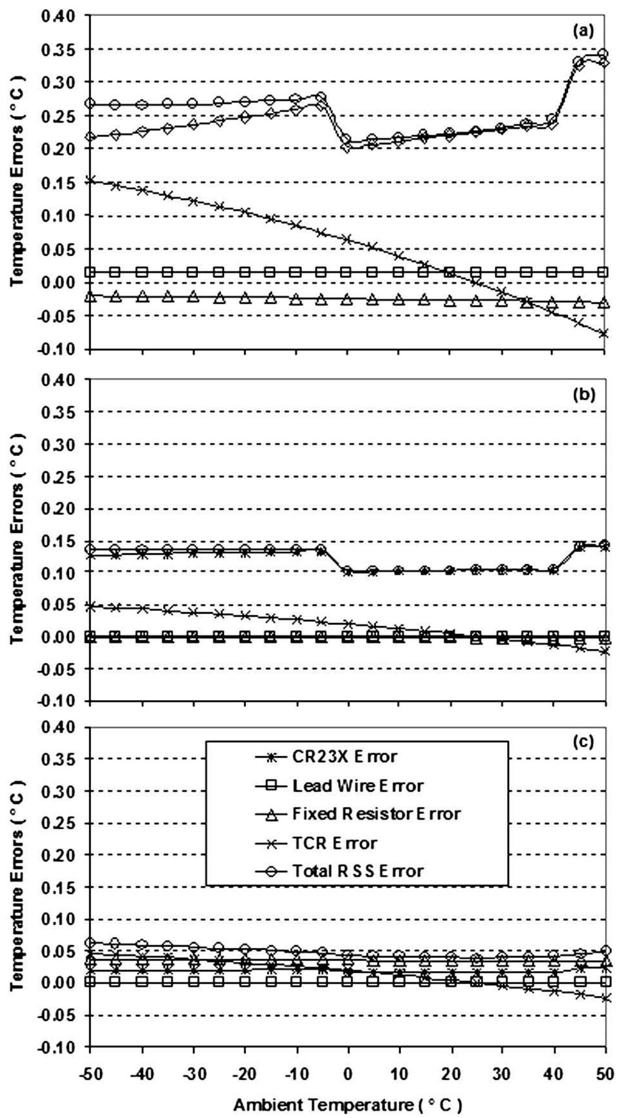

FIG. 4. Temperature error analysis for three USCRN configurations: (a) current USCRN PRT, (b) proposed four-wire half bridge for USCRN PRT, and (c) proposed six-wire full bridge for USCRN PRT.

operating temperature and humidity ranges. For example, the operating temperature of the electrical fan used in the USCRN radiation shield should be capable of providing the steady airflow during extreme low ambient temperatures.

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