1-1-2011

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Harri Latvakoski
Utah State University

Shane Topham
Utah State University

Latvakoski, Harri, and Shane Topham. 2011. "Characterization of Small Industrial Temperature Sensors." Paper presented at ITS9 Conference, Anaheim, CA, March 19-23.

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Harri Latvakoski and Shane Topham

Space Dynamics Laboratory
1695 Research Park Way, Logan, UT 84341

Abstract. The Space Dynamics Laboratory (SDL) has observed, over several years of work with various blackbodies, significant unexplained calibration drifts in some industrial PRTs. With a mandate to build more accurate calibration sources with tens of millikelvin accuracy, SDL began an effort to understand the calibration drifts in small temperature sensors less than an inch long. Testing was performed mainly by cycling PRTs and thermistors through a range of temperatures in a thermal bath, with further results obtained once the sensors were placed in a blackbody. The key result is that temperature sensors routinely drift during thermal cycling, with some sensors drifting more than others. Because even sensors from the same batch can vary, it is important to screen sensors before using. In addition, it is best to calibrate sensors after they are mounted in a fixture, and some PRTs were found to be highly sensitive to handling.

Keywords: Temperature Sensors, PRT, Thermistor, Thermal Bath, Blackbody

INTRODUCTION

Space Dynamics Laboratory (SDL) is a builder of remote sensing (especially infrared) instrumentation for ground, airborne and space applications. Infrared instruments rely on accurate ground and on-board blackbodies for calibration, and blackbodies, in turn, require accurate temperature sensors. Accuracy better than 0.25 K is often desired for SDL applications, and recent Earth observing and climate monitoring missions are aiming for higher accuracy. The Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission currently has the most stringent specifications, with an accuracy requirement of 0.1 K (k=3) for 5 years on-orbit over most of the infrared band.

Only small temperature sensors are compatible with calibration blackbody needs. Flight blackbodies are necessarily of limited size, and even ground blackbodies are generally not compatible with large standard or secondary standard probes. Thus, small industrial temperature sensors are required.

SDL performed a series of tests to better understand the behavior of these small industrial temperature sensors. The results of this testing are described in this paper.

TEMPERATURE SENSOR BEHAVIOR IN BLACKBODIES

SDL and others have observed that temperature sensors do not behave as well as anticipated given manufacturer specifications once placed in blackbodies. Two or more calibrated temperature sensors that are placed on an isothermal piece of a blackbody are often found to deviate by more than their combined calibration uncertainties. In addition, sensors may show significant hysteresis and larger change over time than anticipated. An example of this behavior is shown in Figure 1, which gives the relative temperature readings at several temperatures from 4 PRTs installed in an existing blackbody. Prior to testing, three of these sensors were calibrated at NIST, and the expected calibration accuracy of the PRTs is ~10 mK. The fourth PRT (sensor 3) is a replacement that was not well calibrated before installation. The figure plots blackbody temperature versus temperature measured by sensors 2, 3, and 4 minus the temperature measured by sensor 1.

Since all of the PRTs are located on a part that should be isothermal to ~5 mK according to thermal models, the three NIST-calibrated PRTs should agree to within ~10 mK. However, as shown in the figure, the readings deviated by as much as 170 mK. Furthermore, the fact that the curves show a deviation of 20 mK at about 180 K suggests hysteresis.

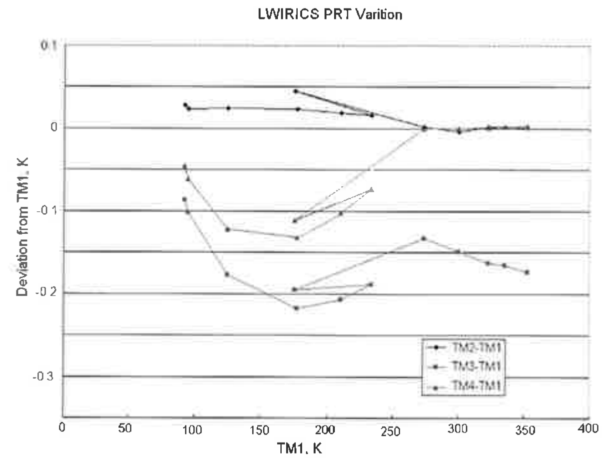


FIGURE 1. Temperature as measured by blackbody-installed sensors 2, 3, and 4 minus that of sensor 1 vs. blackbody temperature.

Because of these observations, SDL performed a series of tests to better understand the unexplained behavior seen in these temperature sensors.

THERMAL CYCLE TESTING

Temperature sensor testing was performed primarily in a thermal bath; additional results were then obtained once sensors were installed in a blackbody. Both PRT and thermistor temperature sensors were tested. PRTs can easily cover the entire 80 K to 350 K temperature range that is commonly needed at SDL and for Earth-observing instruments, and thermistors can cover a significant portion of this range. Both sensors are widely available, have potentially high accuracy, and are relatively inexpensive. Both the calibrated probe used and all the PRTs under test had a resistance of ~100 Ω at 0°C.

The temperature sensor reader used to measure the resistance of the calibrated probe and the PRTs under test has an absolute accuracy of 10 mK over its full resistance range. The thermistor reader accuracy varies with temperature but is generally better than 10 mK.

Thermal Bath Test Setup

The thermal bath used in this study had a temperature range of -45 to 150°C; 10 to 80°C when water was used as the thermal medium in the bath and -40 to 35°C when isopropyl alcohol was used. A calibrated secondary standard PRT in a 12" long probe was used to measure the bath temperature. This probe is calibrated at SDL yearly to an accuracy of 5 mK (k=1). Through repeated cycling from liquid nitrogen temperature to the boiling point of water, and intermittent placement in a triple point of water cell, we found no change in this probe over time.

The sensors under test were placed in the bath by several methods, including placement in individual shrink tubes or plastic bags, or installed in a specialized test piece that holds sensors that are mounted in a fixture and can be put under vacuum. All methods used were demonstrated to effectively keep the sensors at the temperature of the bath. Testing was performed with the sensors located in the middle of the bath near the calibrated probe to minimize the effects of any gradients in the bath.

The typical test involved cycling multiple sensors in the bath over several days. The cycling consisted of holding the bath temperature constant for 1.5 hours at 5 to 9 different temperatures. Figure 2 shows the bath temperature measured by the calibrated probe during a typical cycling test. The bath temperature on the plateaus was found during these tests to be repeatable to ~3 mK in the short term.

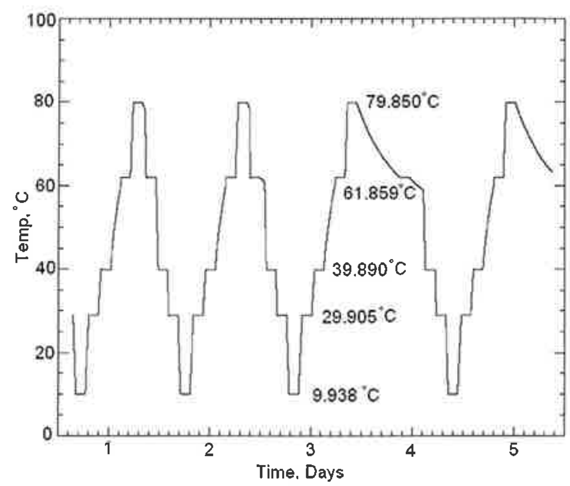


FIGURE 2. Bath temperature as measured by the calibrated probe during a cycling test.

Calibration curves for the temperature sensors under test were then created using the sensors' resistance data and the temperatures from the thermal bath experiments. The PRT curves were fitted using 3 or 5 ITS-90 coefficients, and thermistors were fitted with 3 Steinhart-Hart coefficients. While the number of coefficients may not be sufficient to provide a complete calibration for these small industrial sensors, they are adequate to demonstrate the stability of the sensors. These coefficients were then used to convert the resistance readings from the sensors under test to a temperature that could then be compared to the temperature of the bath as measured by the calibrated probe.

Thermal Cycle Results

Figures 3 and 4 show selected PRT temperature sensor testing data, and Figure 5 shows thermistor data. These figures plot the difference between the temperature readings for each sensor on the plateaus minus the averaged calibrated 12" probe reading on each plateau. For the PRT plots, the black curve near zero represents data from the calibrated probe.

The results generally showed that the temperature sensors drifted over time when the temperature was cycled. The amount of drift varied considerably with individual sensors. In some cases, the drift was consistent with manufacturer specifications, but in other cases exceeded specifications by an order of magnitude or more. Sensors of the same type usually showed similar performance, but exceptions were found, and these exceptions could be more than an order of magnitude worse than others of the same type. The observed drift appears random over time, and the same behavior was observed whether or not the sensor was mounted in a fixture.

A poorly performing sensor, such as that shown in Figure 3, drifted up to 0.5 K, whereas sensors that performed well, such as the types shows in Figures 4 and 5, only drifted at the ~ 1 mK level. Much of the deviation observed in the PRTs in Figure 4 was not drift but was correlated with the bath temperature. There is ~ 3 mK of hysteresis visible in Figure 4, as evidenced by the splitting of the curves in the deviation vs. bath temperature plot (right graph), but for two of the PRTs, once the hysteresis was excluded, the deviation was a function of bath temperature. This indicates that there are too few coefficients used in the conversion from resistance to temperature. The drift with time for this type of PRT is at the 1 mK level.

The thermistors shown in Figure 5 showed no sign of hysteresis and had a very low overall deviation. Most of the variation seen was due to either too few coefficients or the absolute uncertainty in the temperature sensor reader for the calibrated probe.

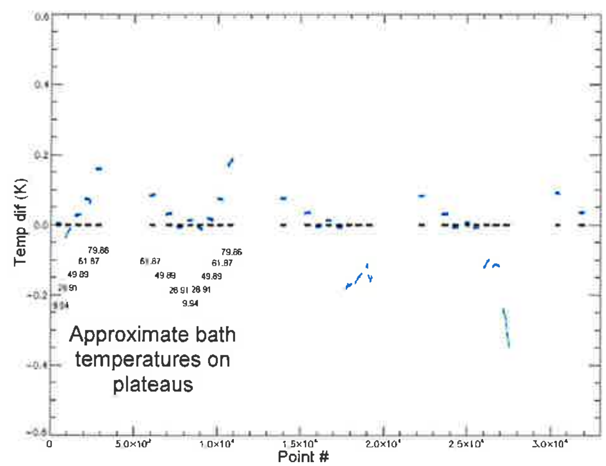


FIGURE 3. Deviation vs. time for a poorly performing PRT (black = calibrated probe, blue – PRT).

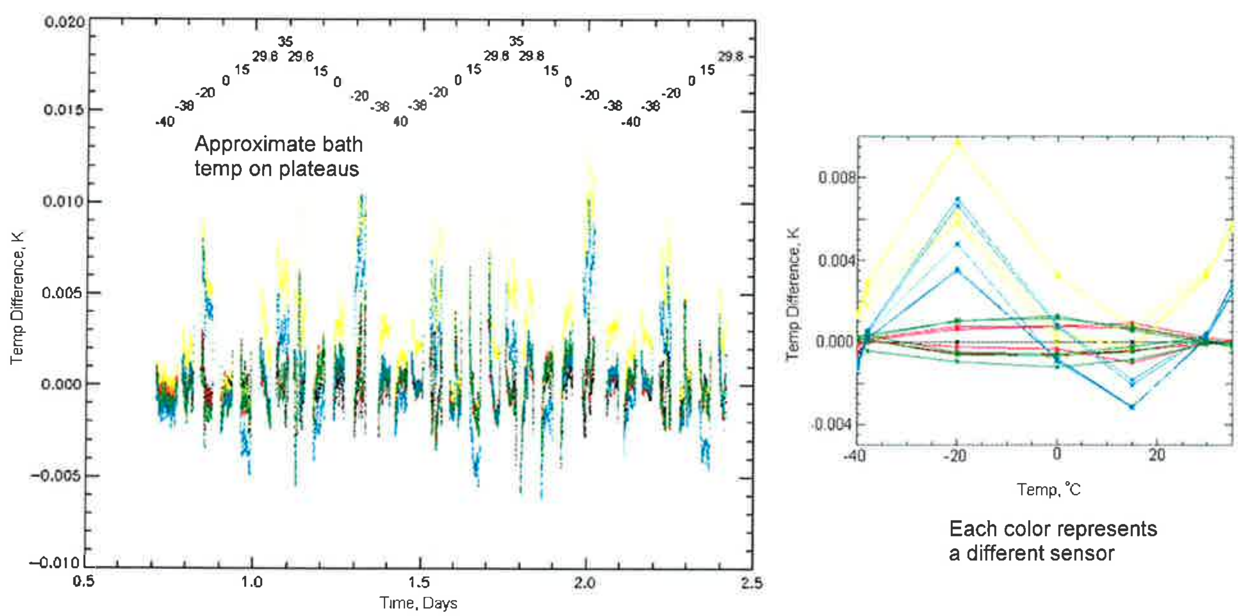


FIGURE 4. Deviation vs. time plot for a set of well behaved PRTs (left) and a plot of the average deviation on each plateau vs. plateau temperature for the sensors (right).

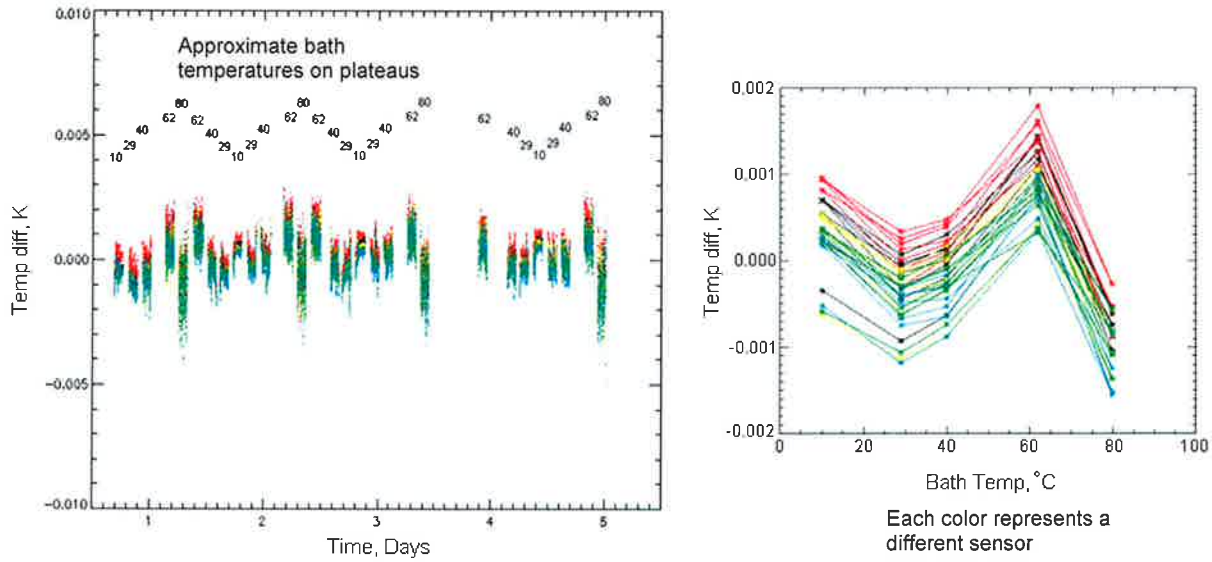


FIGURE 5. Deviation vs. time plot for a set of well behaved thermistors (left) and a plot of the average deviation on each plateau vs. plateau temperature for the sensors (right).

Independent Observations

In addition to the standard thermal cycling tests, selected sensors were cycled repeatedly outside of the bath from liquid nitrogen temperature to the boiling point of water, with intermittent measurements in a constant temperature thermal bath to determine the effect of extreme temperatures on the sensors. These tests showed that while the sensors still drifted over time, the amount of drift was similar to that observed during the standard thermal cycle tests from 9 to 80°C.

Selected sensors were also held at a constant temperature in the thermal bath for several days. In these tests, no drift was observed even in sensors that showed high drift during thermal cycling.

To assess the effects of mounting on these sensors, a PRT and thermistor were tested before and after mounting into a fixture. A change of 10 mK was observed after the mounting. This was expected, and suggests sensors should be calibrated after mounting into a fixture. Tightening these fixtures into a larger mounting piece and putting it under vacuum did not affect the temperature sensor readings.

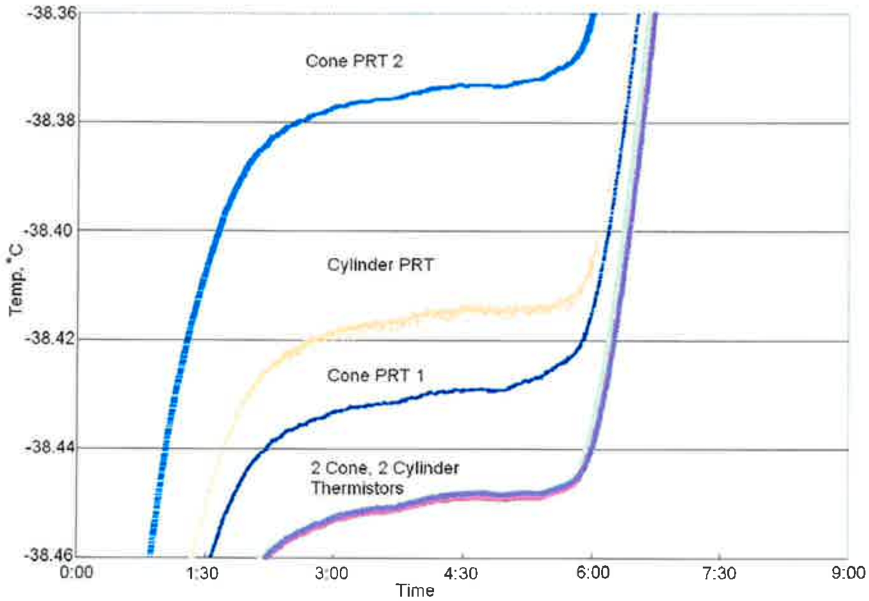
BLACKBODY TESTING

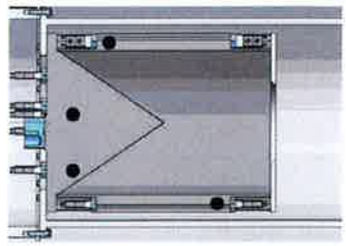
Three different types of temperature sensors were used in the recently built Calibrated Observations of Radiance Spectra from the Atmosphere in the far Infrared (CORSAIR) blackbody[1]: low-drift PRTs with ~ 5 mK of drift over time, high performing thermistors (those used to obtain the data shown in Figure 5), and low performing, but inexpensive PRTs for non-critical locations. Prior to installation in the blackbody, all of the sensors were calibrated from -40 to 35°C using the thermal bath to an absolute accuracy of ~15 mK. During this testing the calibration for the low-drift PRTs changed by up to ~15 mK when they were removed from the bath, subjected to minor handling, and re-tested in the bath. This suggested that these PRTs are highly sensitive to handling. This behavior was not observed in the thermistors or inexpensive PRTs.

Figure 6 shows the behavior of seven of the sensors in the blackbody (three low-drift PRTs and four high performing thermistors) with the blackbody controlled to a constant -38.4°C. Two of the thermistors and two of the high performing PRTs were installed on the blackbody cone with the remainder on an adjacent cylinder. Based on thermal models, all sensors on the blackbody cone should be isothermal to 3 mK. The modeling is not as straightforward for the adjacent cylinder, so it was expected to be anywhere from zero to 10s of mK higher.

Measurements showed that the two thermistors on the cone and the two on the cylinder read within 1 mK of each other at this temperature. At blackbody temperatures varying from -40 to 37°C, the thermistors were always within 4 mK of each other when the blackbody was stable. This demonstrates that no gradient exists across the cone and cylinder under these thermal conditions. It also shows that the thermistors maintained their calibration from the time they were calibrated in the bath to the end of the test because if they had changed, it is unlikely that all of the sensors would have changed equally.

Further evidence that the thermistors maintained calibration was provided by phase change cells in the blackbody[2,3] that allowed the comparison of a thermistor reading to the melt points of Hg, H_2O, and Ga. The thermistor readings were +5, -10, and -17 mK from the known melt points, which is consistent with the expected calibration uncertainty of the thermistors.





Location of sensors (black dots) on the cone and adjacent cylinder of the blackbody cavity

FIGURE 6. Readings from 3 PRTs and 4 thermistors in the CORSAIR blackbody vs. time with the blackbody controlled to a constant -38.4 °C.

While the thermistors maintained calibration, the PRTs readings deviated by up to 70 mK from the thermistor readings, as shown in Figure 6. This supports the notion that the calibration of these PRTs is extremely sensitive to handling. While great care was taken when handling these PRTs, it still suggests that handling caused a change between the final calibration and testing in the blackbody.

SUMMARY AND CONCLUSIONS

Several important results were obtained from the temperature sensor testing at SDL. First, sensors can drift when their temperature is cycled, with some sensors performing better than others. Recently purchased sensors showed low (~1 mK) to moderate (10 mK) drift, while some older sensors ranged from low to extremely high (~0.5 K). This suggests, but does not conclusively show, that drift may increase over time or be a failure mode of these sensors. Sensors should be screened before use, and they should be calibrated after mounting into a fixture. This study also suggests that some types of PRTs are highly sensitive to handling. Finally, one type of thermistor used in this study provided very good performance.

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