8-5-2019

Monitoring Ambient Laboratory Conditions with a Raspberry Pi

Joshua Boman
Utah State University

Physics 4900 Senior Project

Report August 5, 2019

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Joshua Boman

JR Dennison, Mentor

Physics Department Utah State University

Abstract
Precise experimental devices and measurements can be sensitive to changing physical conditions in the lab. The purpose of this research was to develop a standardized computer automated package to monitor and record changes in laboratory conditions, including ambient temperature, atmospheric pressure, relative humidity, light intensity, motion, and power outages. The computer-interfaced device was based around an inexpensive Raspberry Pi microcomputer and commercially available sensors. The Raspberry Pi uploads the sensor data to a file used by LabVIEW to further analyze, plot and display the calibrated sensor data in real time and trigger alarms. This capability allows the Material Physics Research Group (MPG) to track the effects of varying laboratory conditions on experiments conducted in their laboratories. Correlation found between changing laboratory conditions and experimental data can help identify physical conditions that should be better controlled to improve the precision and accuracy of experimental data. Specific examples from the MPG labs are presented. Additional laboratory conditions that will be monitored in the future include AC power fluctuations, vibration, and radiation.

Introduction

This project created an inexpensive computer-automated system to allow real time data monitoring and logging of physical laboratory conditions for the Material Physics Group (MPG). This provides critical information to identify, mitigate and correct influential experimental uncertainties, as experimental apparatus and measurements may be sensitive to changes in the physical laboratory conditions. An inexpensive Raspberry Pi computer and commercially available sensors were chosen for the device, so that multiple devices can be made to inexpensively and efficiently monitor room conditions for the numerous MPG laboratories.

Applications

Monitoring and recording laboratory conditions becomes significant when experimental devices and measurements are sensitive to minute changes in temperature or other physical conditions. Changing laboratory conditions can affect measurements because experimental devices can be sensitive to physical conditions. The physical properties of an experimental sample are also dependent upon the conditions of the laboratory. The extent that these changing physical conditions have on measurements depends on the precision of the measurements taken.

An example where the laboratory monitoring system is useful is the Constant Voltage Conductivity (CVC) chamber. This is used by MPG to measure the conductivity of Highly Disordered Insulating Materials (HDIM). HDIM are polymers that have extremely low conductivities, $\approx 10^{-19}$ $(\Omega\text{-cm})^{-1}$. HDIM are often used to insulate electronic components on spacecraft because of their low conductivities. When they are used for this purpose, HDIM can be exposed to the wide range of temperatures in space. These materials experience an exponential increase in conductivity with an increase in temperature due to a process known as thermally assisted hopping. This is modeled as [1]

$$\sigma_{TAH(T,E)} = \frac{n_c 2 v_{TAH} a q_e}{E} exp\left(-\frac{\Delta H}{k_B T}\right) \sinh\left(\frac{q_e E a}{2 k_B T}\right) \qquad (1)$$

where σ is the conductivity, T is the temperature, E is the applied electric field. n_c, v_{TAH}, a, and ΔH are parameters representing material properties. q_e is the charge on the electron and k_B is Boltzmann's constant. Small changes in temperature have a significant impact on an HDIM's ability to insulate sensitive electronics and prevent arching across spacecraft components. Figure 1. shows the sensitivity of MPG's Constant Voltage Conductivity (CVC) experiment to temperature changes of the sample. The typical +/- 0.5 K daily temperature fluctuations of MPG's laboratory have easily discernible effects on the conductivity of a HDIM sample measured by MPG's CVC experiment.

Thus, it is important that the physical conditions of the laboratory are tracked during an experiment, so that measured physical properties of the sample can be reported along with the physical conditions that that property may depend upon. These laboratory conditions can also be manipulated to characterize the physical response of a sample. MPG has found it useful to manipulate the CVC chamber during experiments so that the change in conductivity of a sample due to changing

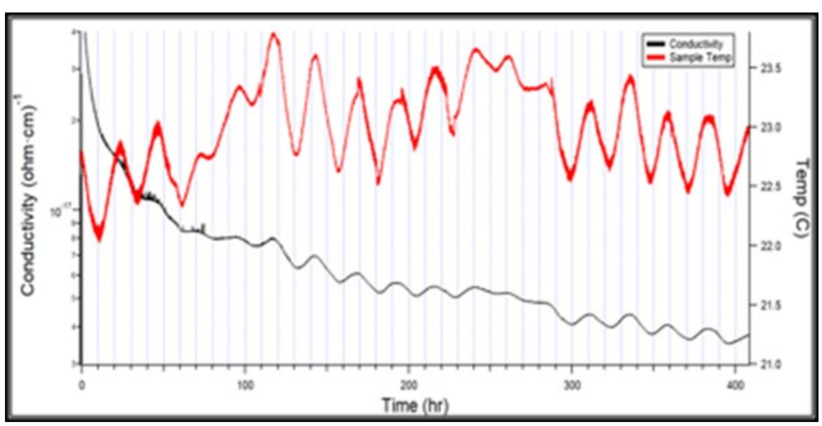

Figure 1. CVC experimental data of conductivity and sample temperature as functions of elapsed time. [2]

Figure 2. Image of Raspberry Pi 3 B+

Figure 3. Image of Adafruit BME 280 temperature, humidity and pressure sensor

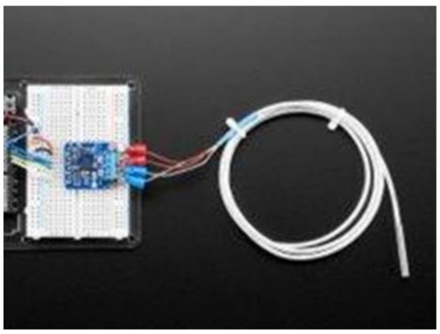

Figure 4. Image of Adafruit PT1000 3 Wire Probe with Adafruit MAX 31865 Amplifier

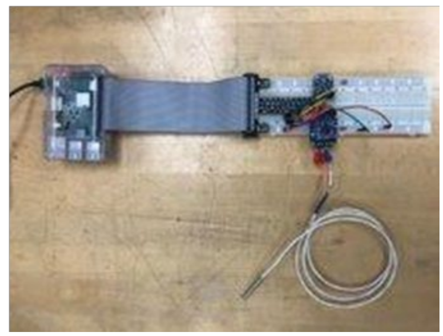

Figure 5. Image of assembled prototype device

temperature can be characterized. It is necessary to have a device capable of monitoring and reporting these temperature changes with accuracy and precision. The device developed in this project will be used in such applications.

Procedure

The commercial components used in this project were a Raspberry Pi 3B+, a platinum RTD probe and a digital temperature, humidity, and pressure sensor. These components are shown in Figures 2-5 and their accuracy and precision are listed in Table 1.

The Raspberry Pi operating system used was *Raspbian Buster*. This was installed using Raspberry Pi's installer, *NOOBS*. This operating system included *Python* 3.7.4. A *Python* program

Table 1. The manufacture specifications for the sensors used in the monitor.[3, 4] It is expected that the accuracy of these sensors will improve with a two point calibration in the range of typical laboratory conditions.

Sensor Reading	Resolution	Accuracy
BME 280 Pressure	0.18 Pa	+/- 0.1 kPa Absolute or +/- 0.012 kPa Relative from (70kPa-90kPa)
BME 280 Temperature	0.01 K	+/- 0.5 K
BME 280 Relative Humidity	0.008% RH	+/- 3% RH
MAX 31865 with PT 1000 probe Temperature	0.03 K	+/- 0.5 K (0.05% of full range)

was written to record the RTD probe temperature, ambient temperature, humidity and pressure. This

program imported *Python* modules created by the sensor manufacturers to create and initialize sensor objects that are called upon by the program. These *Python* modules were installed using *Pip*, *Python's* package installer. The modules used were adafruit_blinka, adafruit_max31865, adafruit_bme280, and numpy. SPI and I2C communication protocols were enabled by running the command raspi-config in terminal and following the onscreen prompts. These must be enabled for *Python* to communicate with the sensors through the SPI and I2C pins on the Raspberry Pi.

A more detailed write up of the *Python* program will be included later, but several important features and general structure are included in this report. The program included a protocol for analysis and filtering of extraneous data to reduce or eliminate sensor error. The sensors were monitored every second for a minute. The average and standard deviation of all of the sensor measurements were taken and the data points were filtered using Chauvenet's criterion to identify points more than three standard deviations outside the mean.[5] The number of outlying data points was recorded. The average and standard deviation were calculated again after the outlying points were filtered. The program created an hourly comma separated value (CSV) file where a new line of comma separated values containing the average, standard deviation, and number of outliers was appended each minute. The program created a time dependent directory for storing the hourly files. This directory contained nested yearly, monthly and daily folders where the CSV files were uploaded. This directory structure was implemented so that the hourly files were stored in an organized form that was easily understood by the user. This directory structure is shown in Figure 6. A *LabVIEW* program was written to read updates from the CSV files and plot the current lab conditions. The front panel of this program is shown in Figure 7.

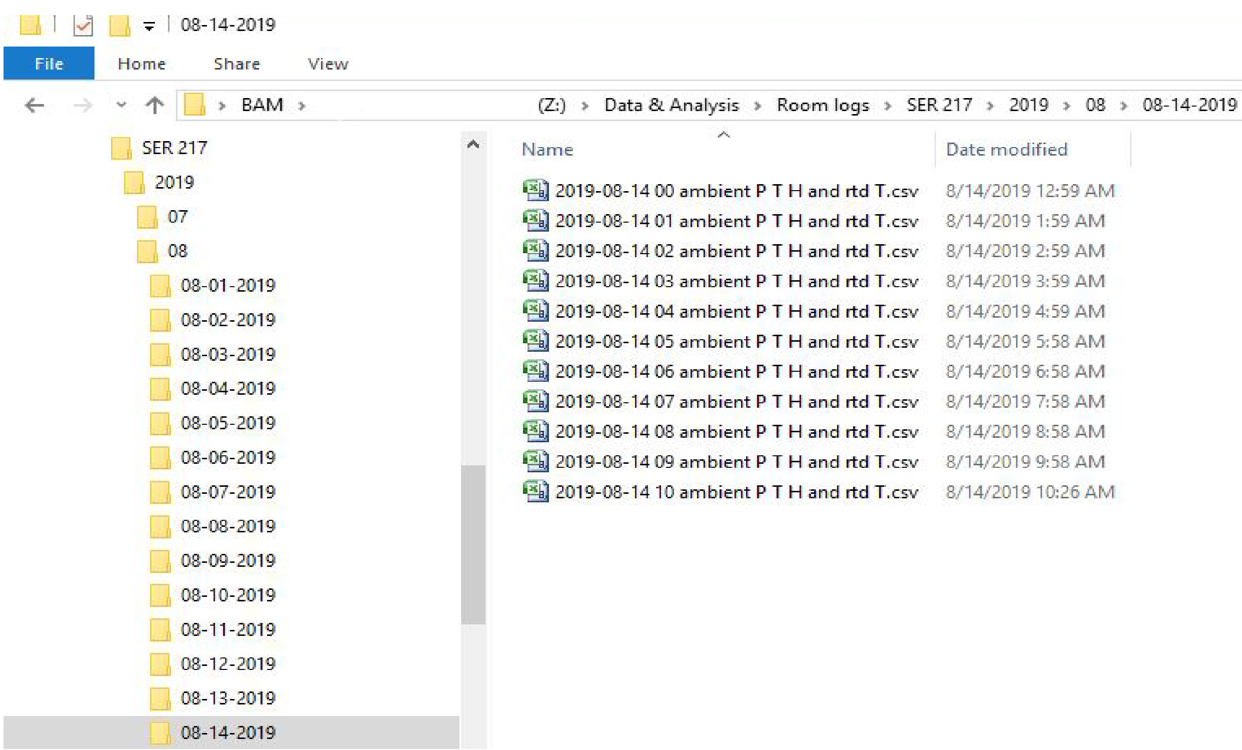

Figure 6. Image of file directory and hourly CSV files.

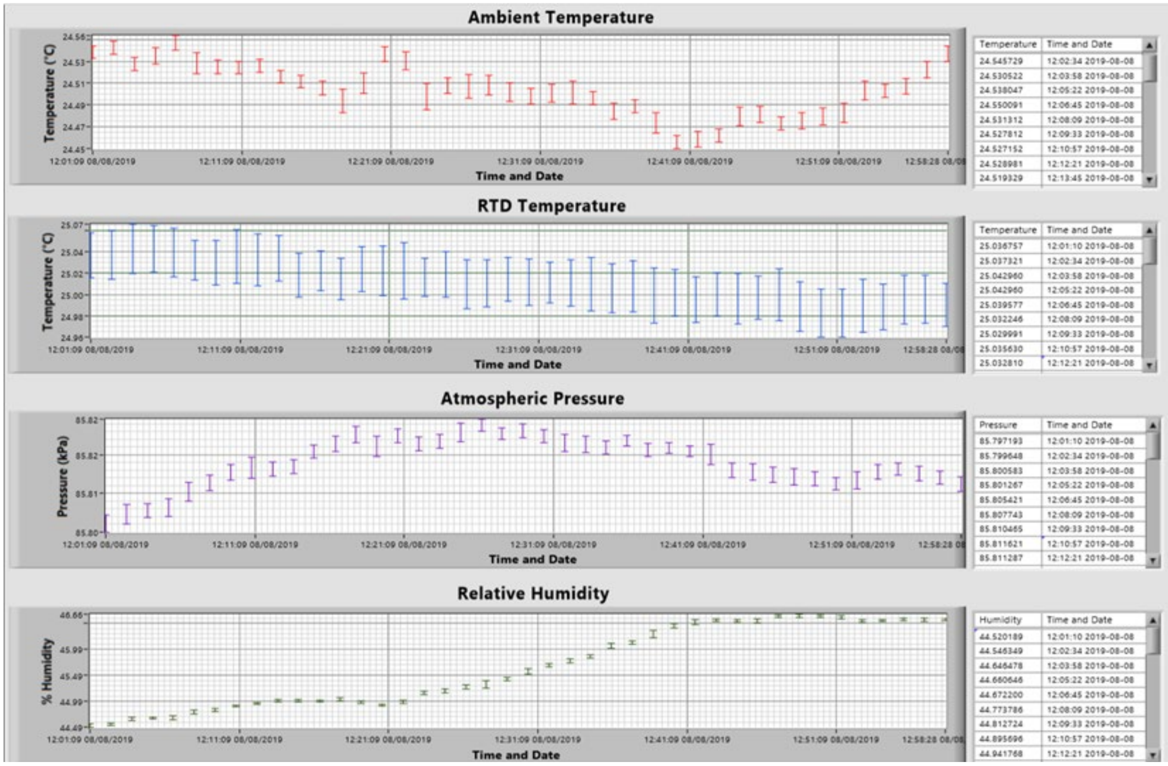

Figure 7. Image of *LabVIEW* front panel.

Data and Analysis

The laboratory monitoring system recorded laboratory temperature, pressure, and humidity for a month. A week of these measurements is plotted in figures 8-11.

Figure 8 illustrates the agreement between pressure measurements taken with the laboratory monitor and those taken by the Utah State University Climatology Center. The offset between these two sets is nearly constant. The offset is dependent on calibration and the altitude change between USU's weather station (1460 m) and MPG's laboratory (1464.75 m) which is on the second floor of the Science and Engineering Research building at USU. The average offset between USU weather station and BME 280 pressure was 0.2678 kPa with a standard deviation of 0.0077 kPa or +/- 3 %. This low standard deviation shows that the BME 280 chip is capable of measuring pressure with precision. The plot of laboratory pressure had to be offset because the BME 280 chip was not calibrated. It is likely that this offset is due to solder drift, which is +/- 0.2 kPa.[3] When the BME 280 chip is calibrated against the USU Climatology Center's barometer the monitor should accurately measure laboratory pressure to within the offset standard deviation of approximately +/- 0.008 kPa or +/- 0.01%. When calibrated, the pressure sensor offset may be a result of the elevation difference between the sensors (estimated to be approximately 0.052 kPa), internal pressure of the SER building due to the ventilation system, or due to sensor inaccuracies.

Figure 9 shows the relation between the temperature recorded by USU's weather station and temperature in the laboratory. It appears that the temperature fluctuations in the laboratory are dependent on the thermostat program. One can assume that the thermostat is programmed to lower the room temperature during typical business hours. Conversely, the temperature does not raise enough overnight to turn on the air conditioning system. During this period, the laboratory

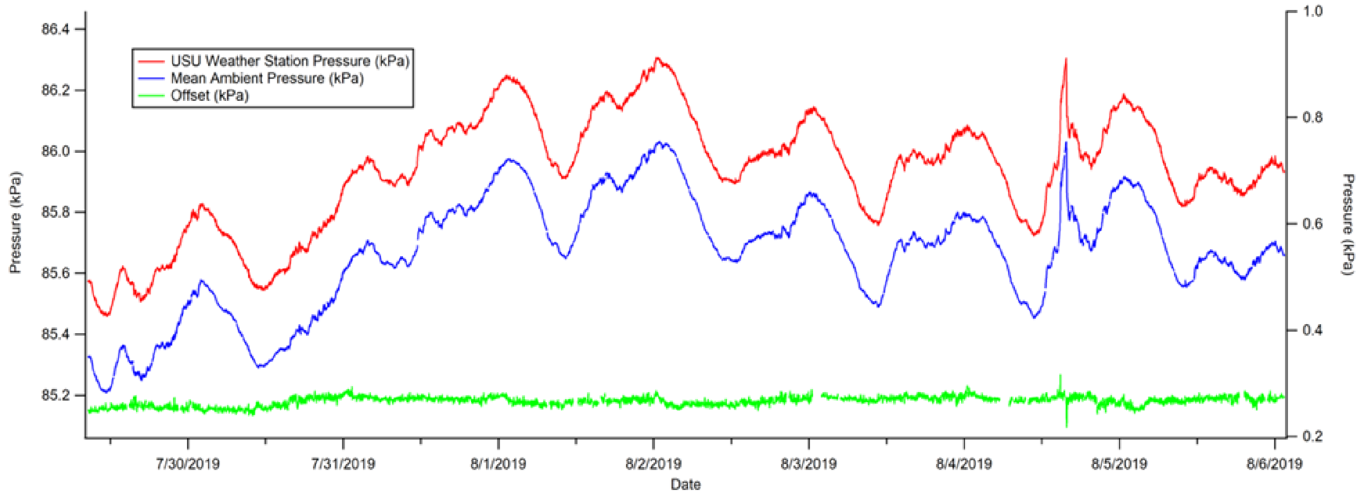

Figure 8. USU campus weather station's pressure, along with the pressure recorded in MPG's laboratory.

temperature comes into thermal equilibrium with the building. Figure 9 shows that the overnight laboratory temperature is dependent on the outdoor temperature earlier that day. A higher afternoon outdoor temperature corresponds to a higher overnight temperature in the lab and vice versa. These data sets were taken during the summer and MPG has yet to monitor fluctuations in the laboratory during the winter. It is assumed that the temperature fluctuations will change when the laboratory is heated in the winter. The equilibrium laboratory temperature may also be dependent on the laboratory's physical location in the building, i.e. labs central to the building may not be as dependent on the exterior temperature fluctuations as those with an exterior wall. It can also be assumed that labs in the basement might have more stable temperature fluctuations.

The offset between the ambient temperature and RTD probe temperature is also shown. This offset has an average value of -0.035 K and a standard deviation of +/- 0.1 K. These sensor temperatures varied because the sensors were not calibrated and the sensors were placed at different

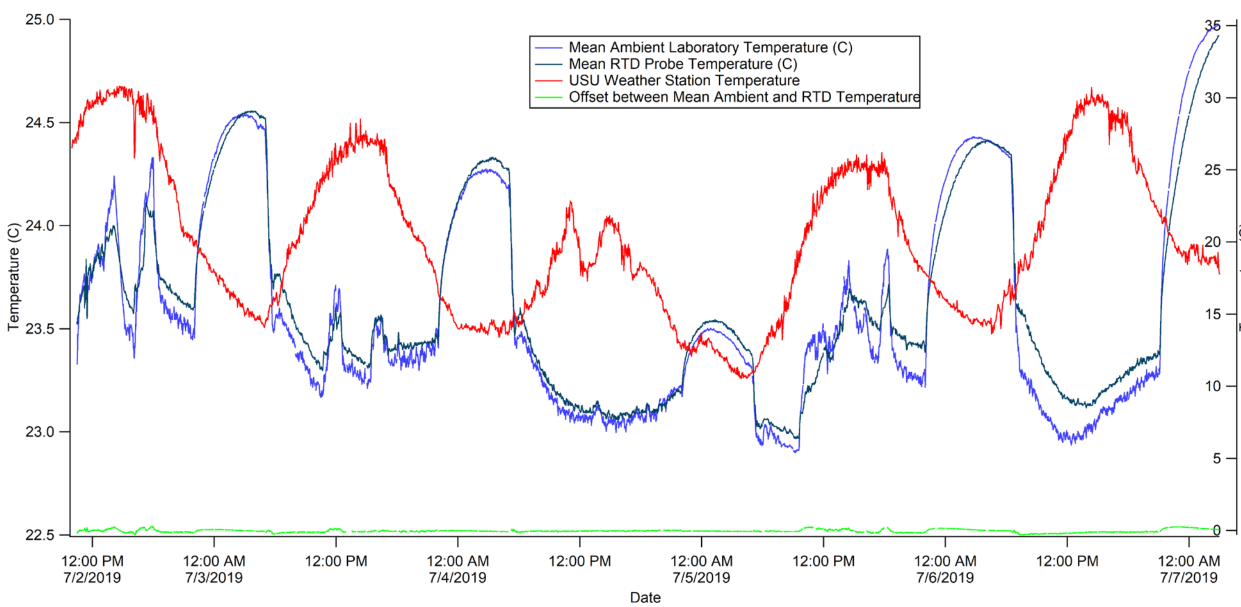

Figure 9. USU Campus weather station's temperature along with the BME 280 and RTD probe temperature recorded in MPG's laboratory.

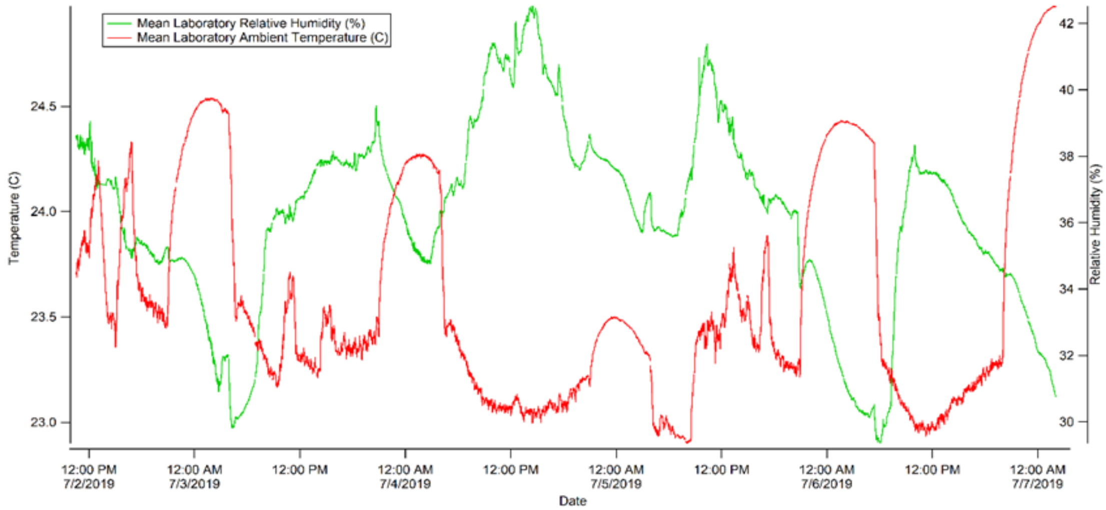

Figure 10. Relative humidity and temperature recorded in MPG's laboratory.

points in the laboratory. The ambient temperature sensor measured air temperature while the RTD probe was resting a wooden tabletop. The sensors will be calibrated in boiling water and an ice bath. This calibration should improve the temperature measurements of the monitor.

Figure 10 illustrates the relation of temperature and relative humidity in the lab. Relative humidity is dependent on air temperature, because with increasing temperatures the amount of moisture that air can hold increases. An increase in ambient temperature of the laboratory causes the relative humidity to decrease.

Figure 11 shows temperature fluctuations of the CVC chamber and the effect on the conductivity of an HDIM. MPG's CVC experiment is capable of measuring the conductivity of a sample four orders of magnitude greater than commercially available systems. It has a sensitivity of

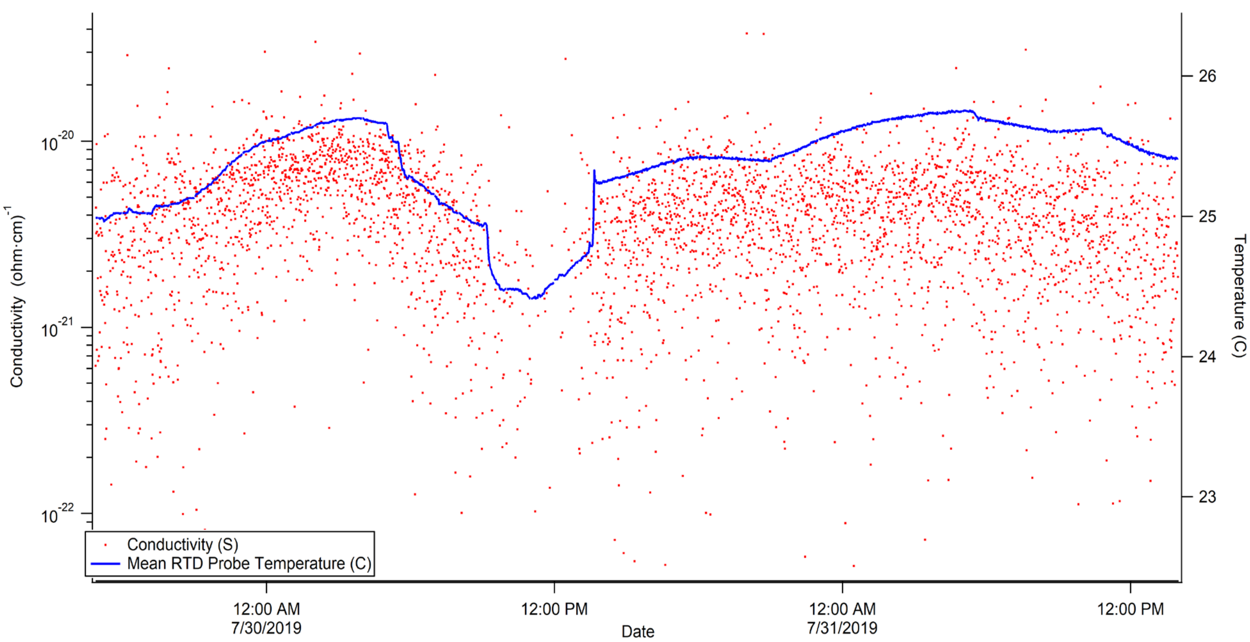

Figure 11. CVC conductivity data taken and the temperature of an RTD probe mounted on the CVC chamber.

about 10^{-22} $(\Omega\text{-cm})^{-1}$. Therefore its measurements are sensitive to small temperature fluctuations on the order of +/- 0.5 K. This required the resolution of the temperature sensors used on the monitor to be on the order of +/- 0.1 K. The resolutions of the sensors used in the monitor met this requirement. However, the sensors should be calibrated at typical laboratory conditions so that the accuracy can be improved beyond the manufacturer's specifications. These calibrated temperature sensors will allow MPG to characterize changes in measured CVC conductivity caused by changing temperature.

Conclusion and Future Work

The laboratory monitoring system created in this project accurately recorded temperature, humidity and pressure for a month. The data recorded agreed with USU's campus weather station and proved that the monitor was accurate and precise. This monitor will be useful for identifying the dependence of MPG's experiments on changing laboratory conditions. Changes in temperature in MPG's laboratory were linked to changes in conductivity in the CVC experiment. This will be useful in characterizing the temperature dependent response of the conductivity of HDIM.

Future work will include adding more sensors to the monitor. Sensors that will be added include a motion sensor, light intensity sensor, AC power outage sensor, and vibration sensor. The *LabVIEW* program will be modified to compile data from the directory so that it can be graphed for the duration of any experiment. A detailed write up of the program will be written so that the program can be easily modified and understood by someone with little coding experience. The sensors used for the monitor will be calibrated for the range of typical laboratory conditions. When these changes have been made, a monitor will be made for each of MPG's laboratories. These monitors will be useful in characterizing the response of physical properties of a sample in MGP's experiments to changing laboratory conditions.

References

[1] J. Brunson, Ph.D. dissertation, Utah State University, 2010.

[2] Megan Loveland, Brian Wood and J.R. Dennison, in *Proceedings of USU SRS*; "Temperature-Dependent Conductivity of Highly Insulating Polymers," (Utah State University, Logan, UT, 2019).

[3] Bosch Sensortec GmbH, "BME 280," BST-BME280-DS001-10, Revised May 2015.

[4] Maxim Integrated Products, Inc, "MAX31865,"19-6478, Revised July 2015.

[5] J.R. Taylor, An Introduction to Error Analysis: the Study of Uncertainties in Physical Measurements (University Science Books, Sausalito, CA, 1997).