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Characterization of a Temperature Measurement System for Use in Vacuum

Master's Thesis
(30 ECTS)
Applied Measurement Science

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List of Abbreviations

Acronym	Abbreviation
TCT	Thermal Cycle Test
TVT	Thermal Vacuum Test
TBT	Thermal Balance Test
RTD	Resistance Temperature Detector
EMF	Electromotive Force
PT	Platinum Thermometer
DAQ	Data Acquisition
ADC	Analog-Digital Converter
DB	D-Subminiature Connector Type

1 Introduction

Satellites operate under severe conditions in space and unlike other man-made devices, it is not possible to perform repairing or maintenance activities on them while in space. This means they have to be tested extensively on the ground before the launch campaign to ensure a successful launch and on-orbit operation [1]. Several types of thermal tests are required for development, performance validation, and to ensure the survivability of the spacecraft in operation. These tests can be performed in components, subsystems, and system levels. The thermal testing usually includes a thermal cycle test (TCT), thermal vacuum test (TVT), thermal balance test (TBT), and the vacuum bake-out test [2]. Thermal vacuum testing is a very important ground test that satellites must pass before launching. In the spacecraft thermal vacuum test process, the important parameters that need to be measured are the temperature of the relevant parts of the test equipment and spacecraft [3].

In order to test space equipment, there is a need for a controlled environment where the parameters affecting the pieces of equipment are controlled to simulate similar conditions as in the environment where the objects will be used. The environment where testing of the specimen is to be done has to be controlled so that the objects will be tested at various specific parameters [4]. A vacuum chamber is one of the facilities that allows selectively specified temperature and/or presuure values to be realized in a closed volume in a working range. It is ideal for testing various equipment under various thermal vacuum conditions. However, establishing with accuracy the metrological characteristics of these temperature-controlled environments can be very difficult as there are a lot of factors that lead to the uncertainty of the measurements [5]. As a result of this, it is required that the vacuum chamber is characterized to specifically validate the performance and the influence of all factors that affect the temperature in the vacuum chamber and to know it working condition [4]. In order to fulfil the requirements of the European Cooperation for Space Standardization (ECSS) standard for thermal vacuum testing, a reliable temperature measurement system is required.

The main objective of this thesis is to considerably improve on the existing measurement system in use at the University of Tartu, Tartu Observatory (TO) while ensuring that the European Cooperation for Space Standardization (ECSS) guidelines are met. The goal includes:

- selecting a temperature sensor suitable for use in the vacuum chamber,

- calibrating the chosen sensors with the existing temperature measurement system available at the Tartu Observatory,
- compare the existing measurement system and the new measurement system,
- perform tests to characterize the new measurement system both in the climatic and vacuum chamber.

This thesis comprises of five chapters, chapter two gives a literature review of the subject, chapter three comprises of the calibration procedure and results, model equation and uncertainty associated with the whole work are given in chapter four while chapter five gives the conclusion.

2 Theoretical Background

2.0 Requirements for Thermal vacuum testing

For space equipment to qualify and get accepted for launching, it has to pass a series of pre-launch tests in qualification and acceptance requirements [6]. A thermal vacuum test is one of the tests done in both the qualification and acceptance stages. Thermal vacuum testing is performed for space segment equipment whose operation occurs in a space vacuum environment at any time of its lifetime [6]. It determines the ability of components, equipment or other articles to withstand rapid changes of ambient temperature and its ability to withstand the maximum and minimum temperatures it experiences during its operation. Thermal vacuum testing consists of thermal cycling the entire experiment assembly in an operating mode. This test is performed to detect problems early in the hardware development. It checks the functional capability of the electronic components in a simulated on-orbit temperature environment [4]. Some of the requirements that must be fulfilled for thermal vacuum testing are highlighted below:

2.0.1 Rate of change of Temperature

The rate of temperature change refers to the speed at which the temperature in the thermal vacuum increases or decreases while thermal cycling the specimen under test. For equipment to be launched in orbit the rate of temperature change is required to be less than 20 K/min [6].

2.0.2 Dwell Times

Dwell times refer to the duration necessary to ensure that internal parts or subassembly of a space segment equipment have achieved thermal equilibrium, from the start of the temperature stabilization phase, i.e. when the temperature reaches the targeted test temperature plus or minus the test tolerance. For equipment to be launched in space, the specimen is required to be exposed to dwell times of at least 2 hours at each extreme temperature in thermal vacuum tests [4], [6].

2.0.3 Tolerance and Accuracy

Tolerance is the limited or permitted range of values of a specified test level without affecting the test objectives. It is typically specified as deviation from a specified value or as an explicit range of allowed values. On the other hand, accuracy depicts the degree of closeness between a measured quantity value and its true value [6].

2.0.4 Extreme Temperatures

Extreme operating conditions refer to conditions that a measuring instrument or measuring system is required to withstand without damage, and without degradation of specified metrological properties when it is subsequently operated under its rated operating conditions. Table 1 below shows the temperature range and some additional requirements [6].

Table 1: Allowable tolerance of test parameters [6].

Test Parameters	**Requirements**
Temperature Range (Requirement not from [6])	(-40……+150) °C.
Temperature Accuracy Above 80 K	±2 K
Temperature Rate of Change	Maximum 20 K/min.
Number of Cycles	4 cycles in qualification, 3 cycles in acceptance (plus one more backup cycle that can be decided during a test).
Vacuum Pressure	10^{-5} hPa or less.
Pressure Tolerances > 1,3 hPa 1,3 10^{-3} hPa to 1,3 hPa < 1,3 10^{-3} hPa	Pressure Tolerances and Accuracy ± 15 % ± 30 % ± 80 %

According to the guideline above [6], no definite temperature range is given for thermal vacuum testing and as such, the customer requirements, requirements from the launch provider, or testing laboratory requirements may suffice. In this study, the temperature range of -40 °C to +150 °C is chosen based on the range in which vacuum testing is performed at the Laboratory of Space Technology at Tartu Observatory. Qualification and acceptance temperature limits are reached when any equipment reaches its qualification and acceptance limits. The qualification and acceptance limits represent the maximum and minimum design temperature and a 5 °C margin [7].

2.1 Sensors.

There are different varieties of sensors used for temperature measurement, but the common types used for space technology applications are Thermistors, Thermocouples, and Resistance Temperature Detectors (RTD) [8]. To select a suitable sensor for any application, there is a need to understand the working principles and pros and cons of each sensor.

2.1.1 Thermocouple

Thermocouples are the most widely used of all temperature sensors as their basic simplicity and reliability have an obvious appeal for many industrial applications [9]. The thermoelectric electromotive force is created in the presence of a temperature difference between two different metals or semiconductors. Thermocouple uses this effect, called the Seebeck effect [9], to detect the temperature difference between the two sources. A thermocouple circuit consists of two metals, e.g. copper and constantan as in the T-type thermocouple, with two junctions which are the test junction and the reference junction. Thermocouples have the widest temperature range of all the sensor technologies, -200 °C to +2315 °C and can be used in a wide variety of environments [10]. The accuracy is typically between 0.5 °C to 5.0 °C with an inhomogeneity error being the largest uncertainty contribution [9]. Figure 1 below shows a thermocouple setup with external reference junction [11]:

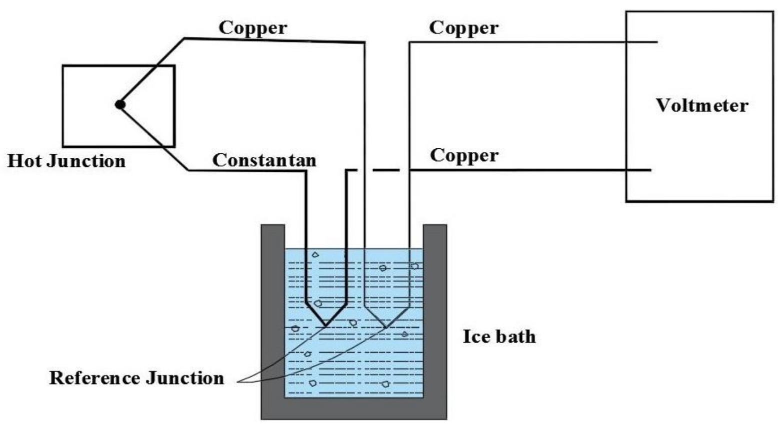


Figure 1: Thermocouple temperature measurement circuit.

One major problem with the thermocouple is that for every connection made to a wire, a new junction is formed and hence a parasitic electromotive force (EMF) is generated as a result of the impurities of the lead wire, soldered connections and temperature non-uniformity [9]. Thermocouple temperature-EMF tables have the ice point, 0°C, as the reference temperature, and this traditional fixed-point temperature is preferred for accurate and reliable measurement [8]. It is not always possible to maintain the reference junctions (commonly called cold junctions) at the desired temperature during the calibration of a thermocouple, but if the temperature of the reference junctions is measured or monitored, it is possible to apply corrections to the observed EMF, which will yield a calibration with the desired reference-junction temperature [8], [9]. If the EMF of the thermocouple is measured with the reference junctions at temperature T, and calibration is desired with these junctions at temperature T_0, the measured EMF may be corrected for a reference-junction temperature of T_0 by adding to the observed value the EMF which the thermocouple would give if the reference junctions were at T_0 and the measuring junction at T [8]. The above is mathematically explained in equation 1 below.

$$E_C = E_M + E_R \quad (1)$$

Where;

E_C is the EMF after applying reference junction correction.

E_M is the EMF with reference junction at T.

E_R is the EMF with measuring junction at T and reference junction at T_o.

2.1.2 Resistance Temperature Detector (RTD)

The resistance temperature detector is another type of temperature sensor which is available in a 2, 3, and 4-wire configurations with identical basic components [11]. Resistance temperature detectors work in such a way that their resistance increases with a rise in temperature due to the positive temperature coefficient of electrical resistance of metals. Resistance temperature detectors are mostly made from platinum, nickel, or copper with the copper and nickel versions operating at lower temperature ranges and are less expensive than platinum. Their normal operation range is −200 °C to +700 °C. In this range, they are both more accurate and have more linear characteristics than thermocouples [9], [11]. The typical accuracy for RTDs is between

0.1 °C and 1.0 °C [9]. For interpolation between calibration points, there is a need to convert the data recorded for the reference thermometer from resistance in Ohms (Ω) to Temperature in degrees Celsius (°C). The most commonly used equation for this is the Callendar-Van Dusen equation. The Callendar-Van Dusen equation describes the correlation between the temperature and resistance of a Platinum thermometer are shown in equation 2 and 3 below [9]:

For t < 0 °C:

$$R_T = R_0[1 + AT + BT^2 + (T - 100)CT^3] \quad (2)$$

For t > 0 °C:

$$R_T = [1 + AT + BT^2] \quad (3)$$

Where:

R_T is the Resistance at temperature T

R_0 is the Resistance at temperature 0 °C

T is the temperature in °C

A, B, and C are the Callendar-Van Dusen equation coefficient.

2.1.3 Thermistors

Like the resistance temperature detector RTD, the thermistor is also a temperature-sensitive resistor. The typical temperature measurement range is from -100 °C to 300 °C. Among these three categories of temperature sensors, the thermistor by far has the largest parameter change with temperature [10]. Thermistors are generally composed of semiconductor materials. Although positive temperature coefficient units are available, most thermistors have a negative temperature coefficient which implies that their resistance decreases with an increase in temperature. The negative temperature coefficient can be as large as several percent per Celsius, allowing the thermistor to detect minute temperature which could not be observed by RTD or thermocouple [12]. The typical accuracy range for thermistors is between 0.1 °C to 1.5 °C. The temperature-resistance curve of thermistors can be described by different equations. The most commonly used equation is the Steinhart-Hart Equation 4 below [9].

$$\frac{1}{T} = A + B\{\ln(R)\} + C\{\ln(R)\}^3 \quad (4)$$

where:

T is the temperature in Kelvin,

R is resistance in ohms,

A, B, and C are the Steinhart coefficients.

Table 2 below shows the comparison of thermistor with thermocouple and resistance temperature detector.

Table 2: Comparison of three temperature sensors [5].

Temperature Sensors	**Pros**	**Cons**
Thermocouples	• Simple, low cost and rugged • No self-heating effects • Short response time to temperature variation. • Wide temperature range	• Low sensitivity to small temperature changes • Low accuracy • Least repeatable • Parasitic EMF at a new junction
RTDs	• Very high accuracy • Stability over a long time • Resistant to contamination	• Slow response time • Sensitive to mechanical influences. • Self-heating effect • Fragile
Thermistors	• Highly sensitive to small temperature changes. • Stable	• Limited range of measurement • Self-heating effect.

2.2 Metrological Traceability

Metrological traceability is defined as the property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty [13], [14]. In this work, traceability is achieved by the direct comparison of the test thermocouples to the reference platinum thermometer (PT-100) which is traceable to SI through the standards of the National Metrology Institute (METROSERT).

2.3 Measurement Uncertainty

Measurement uncertainty is a quantitative indication of the quality of measurement results, without which they could not be compared meaningfully to each other. Uncertainty evaluation is essential to guarantee the metrological traceability of measurement results and to ensure that they are accurate and reliable [13]. Also, measurement uncertainty must be considered whenever a decision must be taken based on measurement results, such as in accepting/rejecting or pass/fail processes [15].

2.4 Calibration

Calibration is an operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication [13]. Calibration can be executed either on a measuring instrument (or system) or on a measurement standard. The calibration of a measuring instrument allows determining the deviation of the indication of the measuring instrument from a known value of the measurand provided by the measurement standard, with associated measurement uncertainty. In other words, the deviation of the indication of an instrument from the conventional "true value" of the measurand is established and documented [11]. There are technical and legal reasons why calibration is performed. Four main reasons for having an instrument calibrated are [11]:

- to establish and demonstrate metrological traceability,
- ensure readings from the instrument are consistent with other measurements,
- determine the accuracy of the instrument readings, and
- establish the reliability of the instrument, i.e., that it can be trusted.

2.5 Methods of Calibrating Sensors.

The method of calibration to be used in this project is the calibration by comparison method. and it entails calibrating the sensor in question against a reference which should exhibit an accuracy which is three to four times the accuracy of the sensor to be calibrated [5]. Both thermometers are placed into a single homogenous temperature source. When placing the thermometers, care should be taken to ensure a small distance between them and that the sensing element (meaning the measuring points) are at the same height. As a temperature source, liquid baths or dry-well calibrators are generally used [16].

3 Methodology and Results

3.0 Sensor Selection

The sensor needed for this work is to be used in a vacuum environment, care must be taken to ensure that the sensor to be chosen can function well in a vacuum chamber. Resistance temperature detectors (RTD) require current to be passed through their sensing element and as such dissipate heat which in turn causes the temperature of the sensing element to increase and this self-heating effect is highly dependent on the immediate environment of the thermometer [9]. In a vacuum environment, no air, no convection, that means that the self-heating effect becomes very large and very difficult to quantify. This effect is even higher with thermistors as the resistance is even higher and thus the self-heating effect as well. Since this effect does not exist with thermocouples, then the thermocouple is deemed to be the most suitable sensor for this task. In this work, the thermocouple to be used needs to meet the following requirements:

- Must be vacuum compatible and should be able to withstand the minimum and maximum temperature without contaminating the space segment element.
- Should be able to work in the temperature range of -40 °C to +150 °C.
- Accuracy of ±0.5 °C.
- Fast response time, fast enough to meet the requirement of not less than 20 K/min.

Different thermocouples like SE000-test accuracy type K thermocouple [17], SSU-MM type T thermocouple sensor [18], and the XF 1230-FAR Lab facility type T thermocouple was analyzed. While the SE000-test accuracy type K thermocouple is designed to work with a dedicated data logger which cannot be used in this work, the SSU-MM type T thermocouple sensor has a temperature range of -196 °C to 400 °C which is deemed to be too high for this task, the XF 1230-FAR Lab facility type T thermocouple was chosen for this task. It has a working range from -75 °C to 250 °C and the accuracy of the thermocouple is ±0.5 °C [19], which is small enough when compared to the required accuracy with room for additional uncertainty.

3.1 Sensor Cable

In order to effectively carry out the temperature measurement in a vacuum, there is a need for a cable that can withstand the maximum and minimum temperature points (-40 °C and +150 °C) without damage and negligible outgassing. As a result, a Teflon insulated cable with a twisted lead and Class 1 cable specification in accordance with EN 60584-3:2008 is used[19]. This cable is made with copper and constantan conductors with an exposed junction for higher sensitivity and quicker response.

3.2 Hardware

3.2.1 System Architecture for Existing Calibration setup.

The diagram below shows the current set up used for calibrating thermocouples in the Laboratory of Space Technology at the Tartu Observatory.

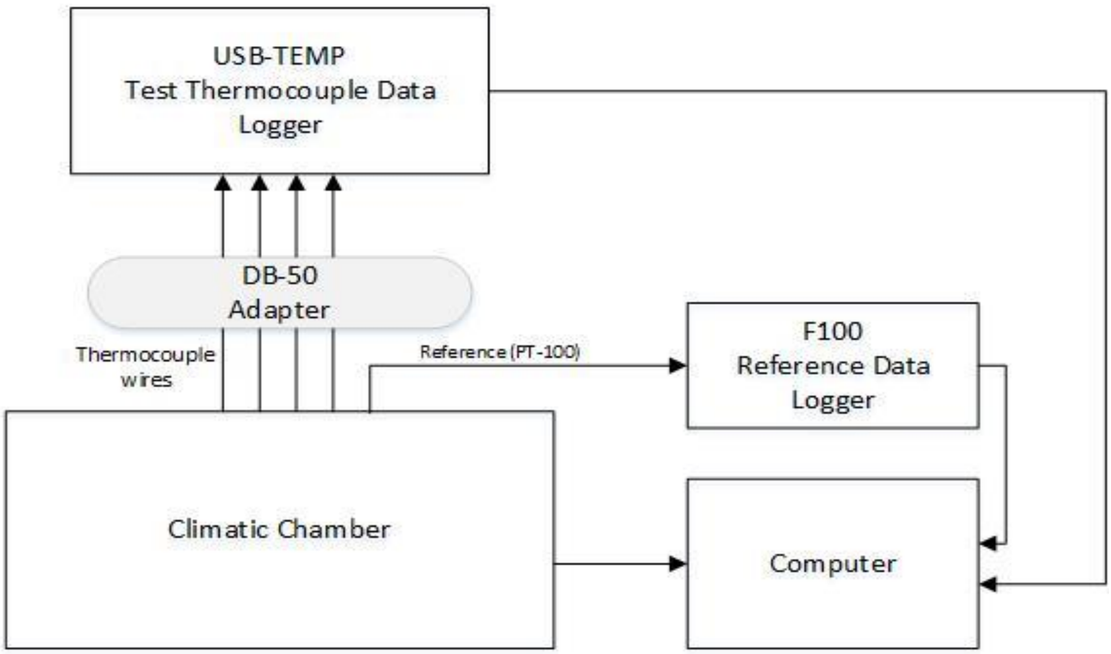


Figure 2: Existing system setup

As seen in figure 2 above, the setup consists of a climatic chamber that serves as a thermal source for calibrating the test thermocouples, a D-Subminiature 50 (DB-50) adapter which serves an electrical interface for connecting the test thermocouples inside the climatic chamber to readout device located outside the climatic chamber. The USB-TEMP and the F100 precision thermometer are data acquisition devices for the test thermocouples and the reference PT-100 respectively. The desired parameters in the climatic chamber are remotely set using a software known as the Simpati software installed on the computer [20].

3.2.2 Climatic Chamber

A Weiss Technik WKL 64 Climatic chamber at Tartu Observatory was used to provide a controlled thermal environment for calibrating the thermocouples. It has an operational temperature range of -40 °C to +180 °C. The chamber has internal dimensions of height 400 mm, a width of 470 mm, and a depth of 345 mm [21].

3.2.3 Data Logger

A Multi-Sensor Temperature measurement USB-TEMP data logger manufactured by Measurement Computing Cooperation (MCC) is used in this task. It supports data acquisition from thermocouples, RTDs, and thermistors. It provides a 24-bit analog-to-digital converter for each pair of analog input channels while up to eight temperature sensors can be connected to the differential sensor input. The logger can read two samples per second. It can acquire temperature, resistance, and voltage data from the sensors [22]. Figure 3 below shows the picture of the data logger used in this task.

Figure 3: Picture of the USB-TEMP

3.3 Software

To effectively calibrate the thermocouples, there is a need to design a means through which data can be logged from both the thermocouple and the reference PT 100 simultaneously. To achieve this, a python script was written and made available to the author. The script automatically stores the data logged by the data acquisition device used for both the reference and the test thermocouple.

3.3.1 Simpati Software

For setting and controlling the temperature of the chamber, the Simpati software made available by the manufacturer of the climatic chamber was used. This software enables setting test parameters such as temperature, pressure, etc. remotely [20].

3.4 Reference Platinum Thermometer (PT-100)

RTD sensors are the elements that react almost linearly to the influence of temperature [10]. They are mostly made of platinum which is one of the best materials for sensors because of its high melting point, great temperature coefficient, small chemical activity, and stable thermometric characteristics. The reference PT-100 used in this work has the following specification.

Table 4: Specifications of reference PT-100 [23].

Parameters	Specifications
Manufacturer	Automatic System Laboratory (ASL)
Serial Number	P0111313-1-14
Type	T100-450-ID
Measurement Range	-200 °C to 450 °C
Drift	0.003 °C
Sheath Material	316 Stainless steel
Expanded Uncertainty (*k*=2) -40 °C - +200 °C +200 °C - +250 °C	 0.02 °C 0.04 °C
Probe length and diameter	355 mm and 6.35 mm.
Date of the last calibration	22.08.2018

3.5 F100 Precision Handheld Thermometer

The F100 precision thermometer handheld thermometer is high precision temperature instrument designed for laboratory temperature measurement and calibrations applications. It is manufactured by the Automatic Systems Laboratory and with user selectable temperature measurement units in °C, °F, K and Ω. It consists of two input channels, a large LCD display for excellent viewing of temperature measurement values and settings, a USB communication Interface as standard for automated monitoring and calibration applications. The F100 can operate with 4-wire Platinum thermometers (PT-100) and virtually all thermistors [24].

3.6 Calibration of Sensor in the climatic chamber

The thermocouples were calibrated by comparison to a standard reference thermometer (PT-100) traceable to the units of SI through the standards of the National Meteorology Institute (METROSERT). Before the calibration was carried out, the thermocouples were visually inspected for obvious mechanical defects and contamination, etc. Also, every thermocouple to be calibrated should be as homogenous as possible inhomogeneous thermocouples used under different conditions from which they were calibrated, especially different temperature gradients will give an erroneous result that could amount to systematic deviations of several degrees Celsius [16]. To achieve the best result, the thermocouples were heat-treated at the maximum immersion temperature of 150 °C for approximately 4-hours after which measurements were recorded from the highest to the lowest temperature points required for calibration [16]. The F100 standard thermometer was used for the acquisition of the data from the reference platinum thermometer (PT 100) while the USB data acquisition device was used for data acquisition from the test thermocouples. The specifications for both data acquisition devices are given in Table 5 below:

Table 5: Specifications of auxiliary read-out devices[22], [24].

	F100 Standard thermometer	**USB-TEMP Data logger**
Manufacturer	ASL	MCC
Resolution	0.001 °C	24 bits
Stability	<0.005 °C / Year	N/A
Measurement range	-200 °C to +850 °C	-270 °C to 400 °C
Accuracy Expanded Uncertainty, k=2	±0.02 °C	±0.514 °C (-200 °C to 0 °C) ±0.256 °C (0 °C to 600 °C)

For effective calibration of the thermocouples, an equalization block made from a cylindrical copper rod with a diameter of 20 mm and 20 mm long was used for good conductivity. A 7 mm hole is on the equalization block where the reference probe with a diameter of 6.5 mm was inserted. Four thermocouples were then firmly placed around the equalization block using a kapton tape to ensure that there is good contact and effective heat transfer between the equalization block and the test thermocouples (see Figure 4). The kapton tape is ideal in vacuum environment as it exhibits a low outgassing property. The sensors and the equalization block were then placed inside the climatic chamber. The reference junction of the thermocouple was soldered to the D-subminiature (DB-50) adapter. A compensating cable whose other terminal was soldered to the other side of the DB-50 adapter was connected to the USB-TEMP. Temperature values and corresponding resistance values were then recorded from the USB-TEMP device and the F100 standard thermometer for both the test thermocouples and PT 100 respectively at ten temperature points ranging from -40°C to 150°C. These points were chosen because thermal vacuum testing at Tartu Observatory is offered to clients in this range. Figure 4 below shows the sensor equalization block that was used, the arrangement of the sensors on the block, and the position of the equalization block in the climatic chamber before calibration.

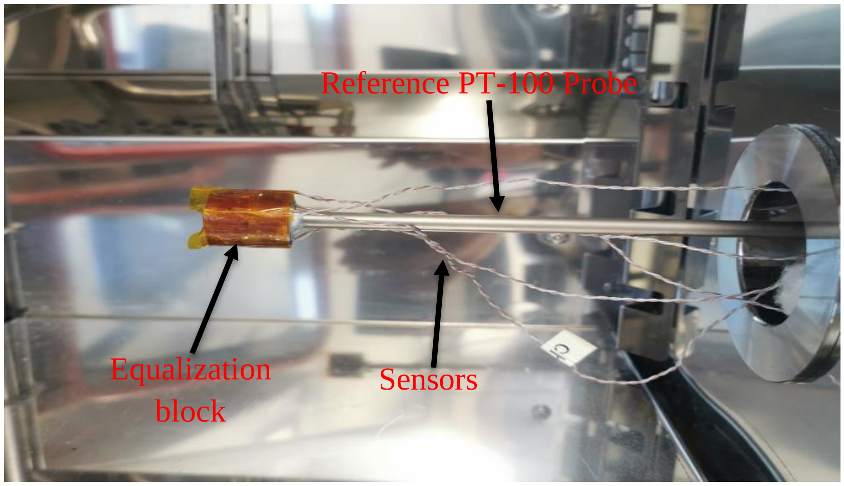


Figure 4: Arrangement of sensors around the equalization block

Data recorded for the test thermocouples at each temperature point was evaluated for autocorrelation which is the correlation between values of the same variable. This is necessary to detect non-randomness in the data and to identify an appropriate time series model if data is not random. To do this, consider the temperature measurement *Y* at time *t*, the lag *k* autocorrelation function is given in equation 5 as [25]:

$$r_k = \frac{\sum_{i=1}^{N-K}(Y_i - \bar{Y})(Y_{i+k} - \bar{Y})}{\sum_{i=1}^{N}(Y_i - \bar{Y})^2} \quad (5)$$

The autocorrelation equation above shows the correlation between values of the same variables at time t_i, t_{i+k}, and the number of measurements taken *N*. When autocorrelation is used to detect non-randomness, it is the first lag 'lag 1' i.e. $k=1$ that is usually of interest [25]. The autocorrelation coefficient for each of the four-thermocouple data was evaluated and the result is shown in table 6 below:

Table 6: Lag 1 autocorrelation coefficient for thermocouples.

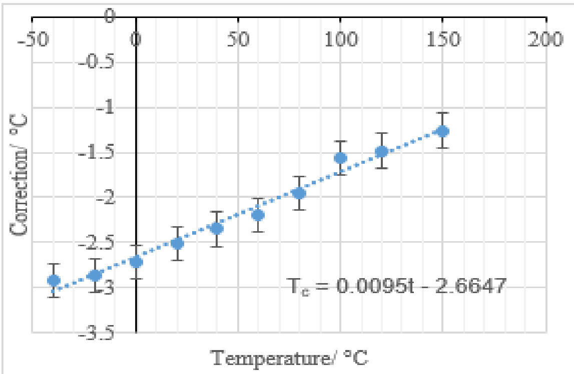
	T1/ °C	T2/ °C	T3/ °C	T4/ °C
Autocorrelation function	0.53	0.49	0.50	0.50

The value for correlation function r_k is usually from 0 to 1 with data being highly correlated at 1 [24]. The autocorrelation function calculated for the four thermocouples T1-T4 is deemed to be uncorrelated as it ranges from 0.49 to 0.53 which is enough for non-randomness. To minimize the drift in the measurement, temperature values recorded for the test thermocouples at each data points for all the set temperature points were subtracted from that of the reference thermometer. The average was calculated for each temperature point and the result presented in Table 7 below.

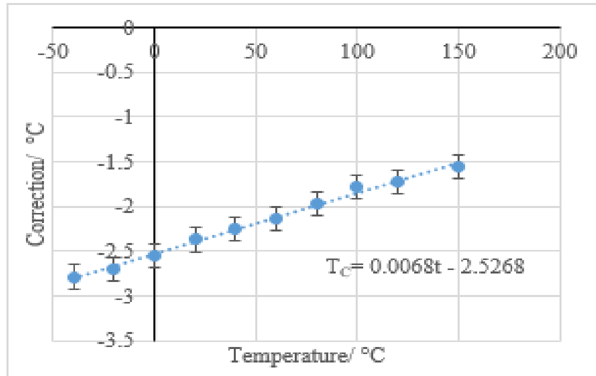
Table 7: Correction values for calibrated thermocouples.

Set Temperature / °C	**(Tref-T1)/ °C**	**(Tref-T2)/ °C**	**(Tref-T3)/ °C**	**(Tref-T4)/ °C**	**Standard Deviation/ °C**
150	-1.26	-1.56	-2.03	-1.74	0.06
120	-1.48	-1.73	-2.14	-1.94	0.02
100	-1.56	-1.78	-2.12	-1.95	0.03
80	-1.95	-1.96	-2.43	-2.43	0.02
60	-2.20	-2.14	-2.59	-2.64	0.02
40	-2.35	-2.25	-2.63	-2.72	0.02
20	-2.51	-2.37	-2.63	-2.78	0.02
0	-2.71	-2.54	-2.73	-2.86	0.03
-20	-2.86	-2.70	-2.67	-2.79	0.04
-40	-2.93	-2.78	-2.50	-2.63	0.02

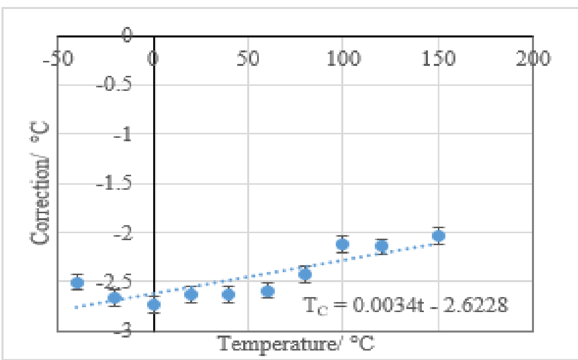
After a thermocouple has been calibrated, the next requirement is convenient means of obtaining correction value for all other points, this is done by computing an equation through the calibration points by direct interpolation between the measurement points [8]. Figures 5a-5d below shows the correction line for thermocouples T1-T4 while the dwell time in climatic chamber is presented in appendix 1.



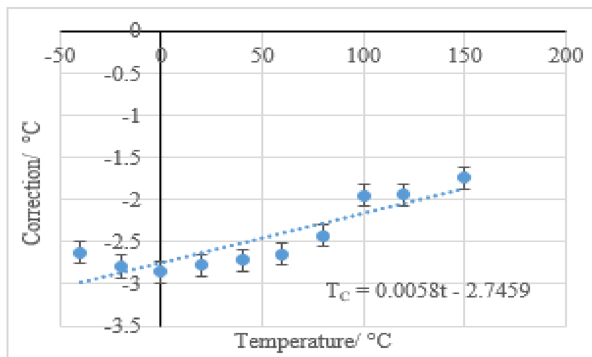
a: Thermocouple T1



b: Thermocouple T2



c: Thermocouple T3



d: Thermocouple T4

Figure 5a-5d: Correction lines for thermocouples T1-T4.

From Figure 5a, the curve fit shows that for every temperature value taken with the thermocouple, the correction $T_c = 0.0095t - 2.6647$ must be applied. This correction can be applied by substituting whatever temperature value measured as *t* in the equation and correction applied accordingly. The error bars depict the type A uncertainty associated with the correction values at each temperature point and it achieved by calculating the standard deviation for the whole temperature value recorded at each temperature point after stabilization. Because the accuracy of the thermocouple according to the manufacturer's specification is within ±0.5 °C, with an average systematic correction of -2 °C for all sensors and points, the system needs to be addressed with further analysis. To achieve this, some possible solutions were suggested, and they are listed below.

- To connect thermocouples differently, and

- calibrate thermocouples with a new data logger.

3.6.1 Direct Connection of Thermocouple to Data Logger.

To ascertain the sources of error in the result of the previous calibration, the calibration set up was done differently and this involves connecting the thermocouple directly to the data logger as seen in figure 6 below.

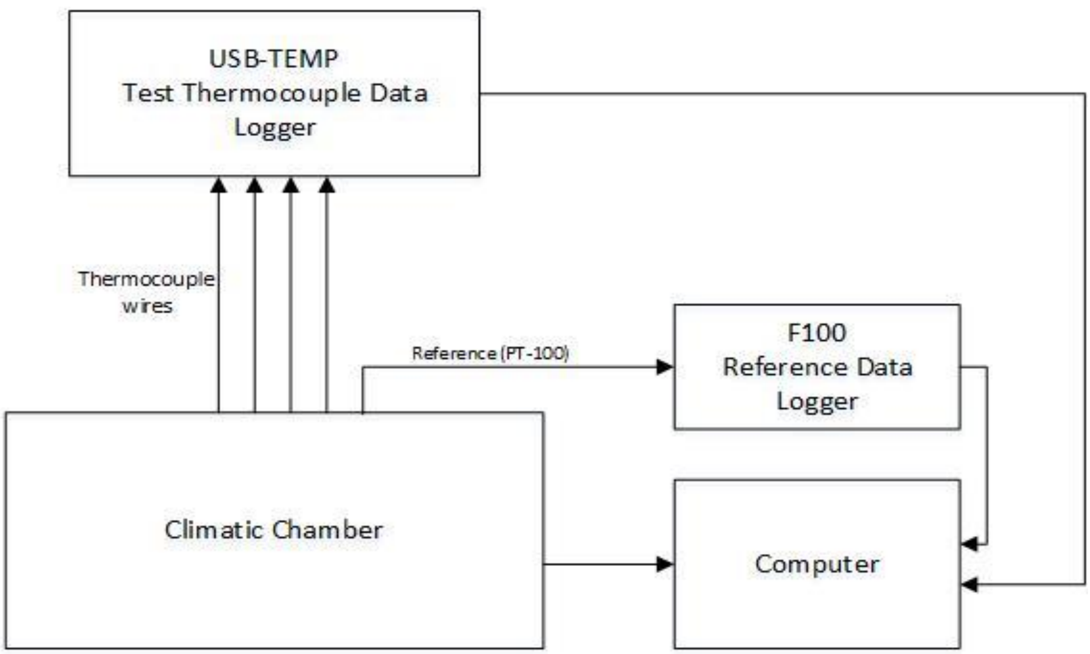


Figure 6: Direct connection of thermocouple to the USB-TEMP.

Here, one thermocouple was connected directly to the USB-TEMP with the reference PT-100 connection left as it was in the previous calibration, and measurements were taken at seven temperature points between -40 °C and 80 °C. The data was analyzed as done in the previous calibration and the results presented as in table 8 below:

Table 8: Correction values for calibrated thermocouple.

Set Temperature/ °C	(Tref-T)/ °C	Standard Deviation/ °C
80	-0.57	0.06
60	-0.53	0.03
40	-0.62	0.06
20	-0.60	0.04
0	-0.68	0.07
-20	-0.56	0.05
-40	-0.53	0.08

The correction line below (see Figure 7) was plotted using table 8 presented above, the dwell time is also presented in appendix 2:

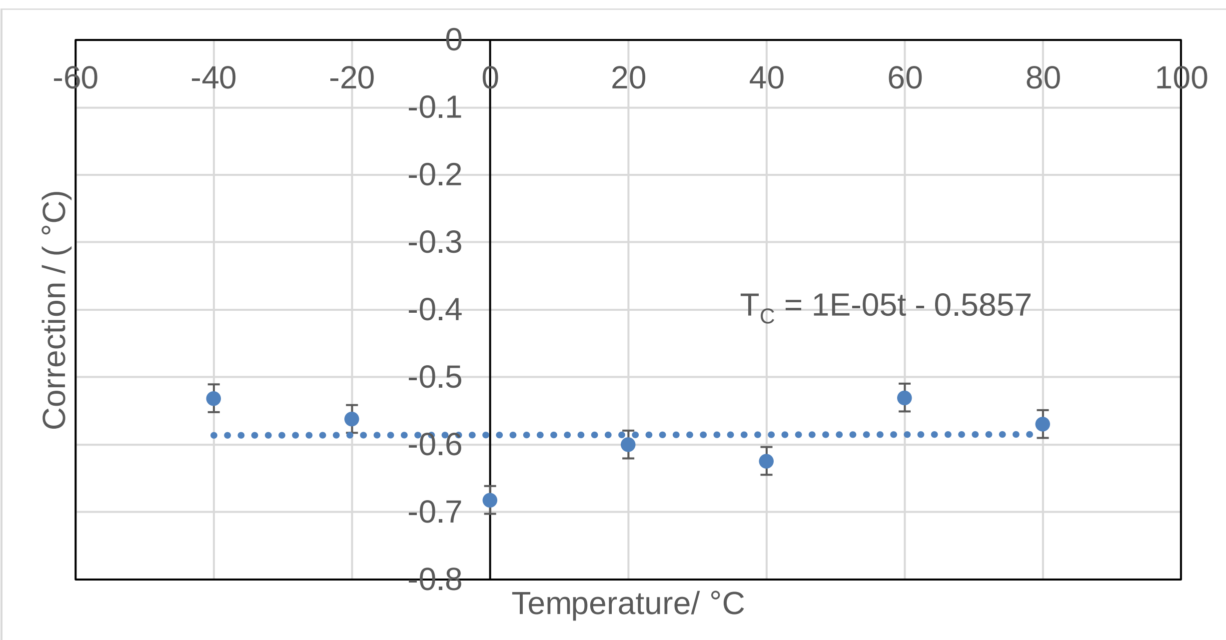
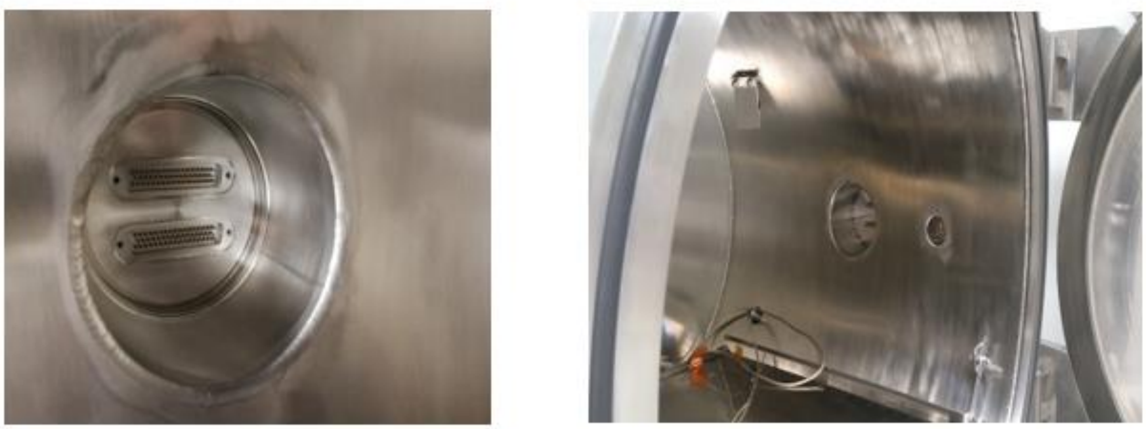


Figure 7: correction line for direct connection of thermocouple.

With the direct connection of the thermocouples to the readout device, the error from the curve fit using this setup compared to that of the previous calibration set up has reduced (see Figure 5 and 7). But for calibration in a vacuum chamber, the DB-50 adapter (see Figure 6a and 6b) used in the first calibration set up is required as it serves as an electrical interface for connecting the thermocouples (inside the vacuum chamber) to the USB-TEMP (outside the vacuum chamber). This is important because the USB-TEMP is not vacuum compatible as it is covered with plastic material and has an operating temperature range of 0 °C to 70 °C [21], therefore usage above this temperature range can lead to outgassing in vacuum which in turn can contaminate the vacuum chamber and the device under test. Due to the reasons above, the calibration by direct connection of the thermocouples cannot be used with the current data acquisition device available even though it is more accurate, as such, a new data acquisition device is required for a more accurate calibration of the thermocouples in the vacuum chamber. Figure 8a and 8b shows the position of the DB-50 adapter on the vacuum chamber.



(a) (b)

Figure 8 (a) and (b): Location of DB-50 adapter on the vacuum chamber.

3.6.2 Thermocouple Calibration with a New Data Acquisition Module.

In order to be able to calibrate the thermocouples in a vacuum, an alternative data acquisition module was used. This module enables the recording of temperature data from 16 channels simultaneously. Figure 9 below shows how the temperature measurement is done using the new data acquisition module.

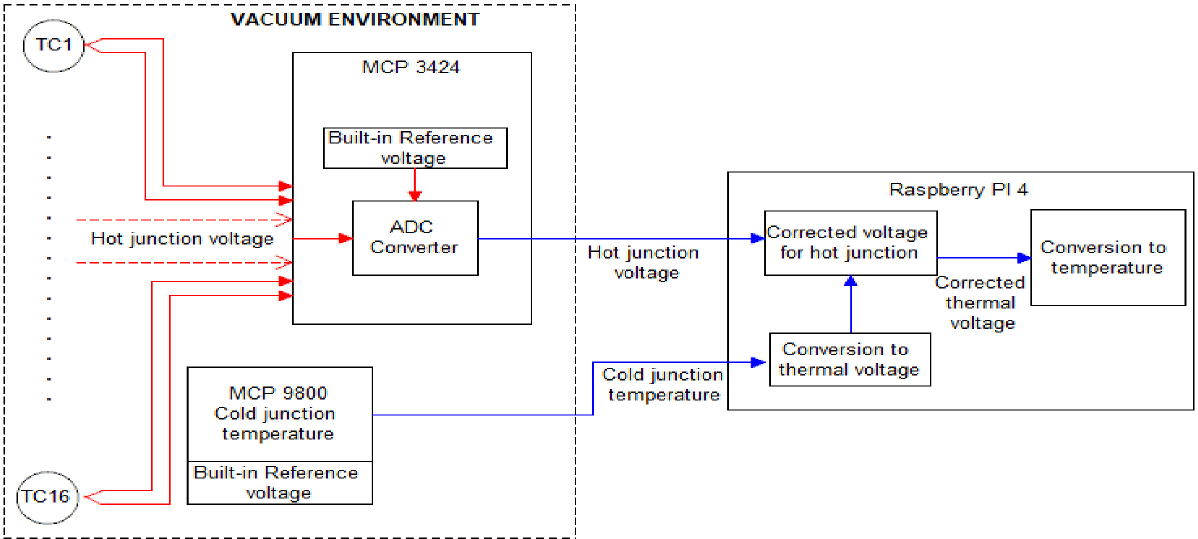


Figure 9: Data acquisition process with new DAQ (Diagram by Mari Allik)

From the block diagram above, the voltage of the hot junction is measured by the MCP 3424 analog-digital converter chip while the temperature of the cold junction is measured by the MCP 9800 temperature sensor chip. The temperature of the cold junction is converted to thermal voltage in digital form using an approximate equation embedded in the data acquisition device [26], [27]. The reference voltage which is built-in to the MCP 3424 AD converter also enables the correction of the voltage value measured at the hot and cold junctions of thermocouples. Then the cold junction is compensated, and the temperature of the hot junction is then logged.

For calibration with the new data acquisition module, four thermocouples were connected as done in section 3.5.1 and the data for ten temperature points (-40 °C to +150 °C) were logged with the new data acquisition device. Figure 10 below shows the new data acquisition module.

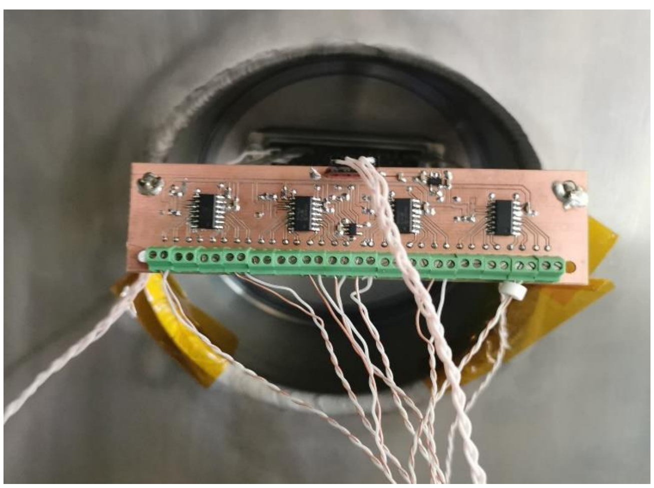


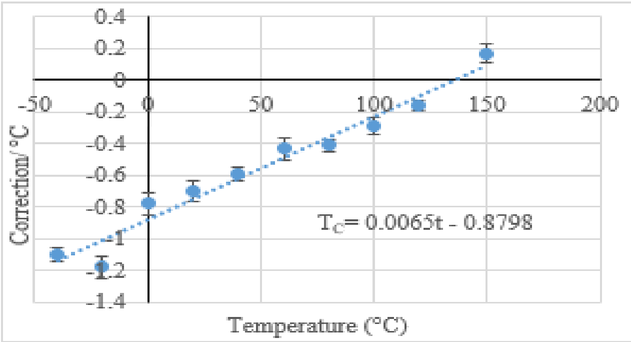
Figure 10: new data acquisition module

The data collected with the new device was collected and analyzed, the results are shown in table 9 below.

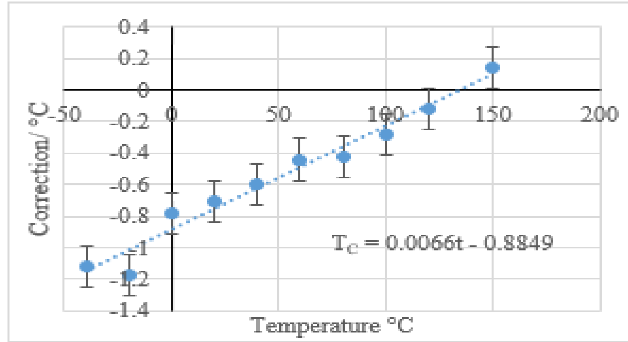
Table 9: Correction data for the thermocouples with new DAQ

Set Temperature /°C	(Tref-T1) /°C	(Tref-T2) /°C	(Tref-T3) /°C	(Tref-T4) /°C	Standard Deviation/ °C
150	0.17	0.14	0.32	0.34	0.06
120	-0.16	-0.12	-0.13	-0.16	0.03
100	-0.29	-0.28	-0.22	-0.36	0.06
80	-0.41	-0.42	-0.50	-0.40	0.04
60	-0.43	-0.44	-0.52	-0.43	0.07
40	-0.59	-0.60	-0.68	-0.60	0.05
20	-0.70	-0.71	-0.78	-0.72	0.07
0	-0.78	-0.78	-0.86	-0.81	0.07
-20	-1.18	-1.17	-1.29	-1.26	0.07
-40	-1.10	-1.12	-1.22	-1.21	0.05

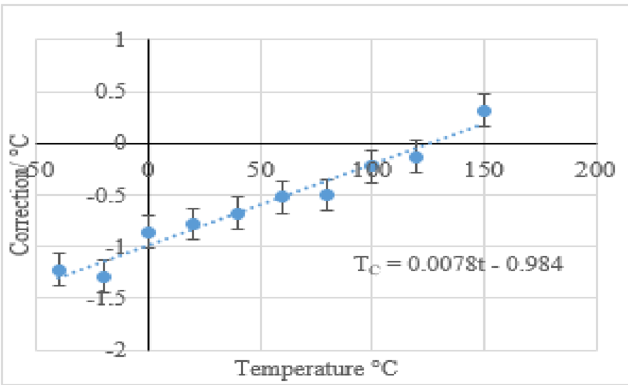
Again, the correction line for thermocouples T1-T4 is shown in Figures 11a - 11d below.



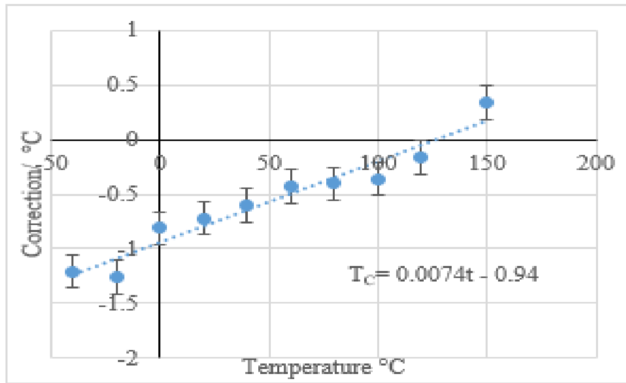
a: Thermocouple T1



b: Thermocouple T2



c: Thermocouple T3



d: Thermocouple T4

Figure 11: Correction line for calibration with the new DAQ

From the figure above (see figure 11a-11d), average systematic correction of about -1 °C still exist between all sensors and points. This systematic effect can be minimized by further improving the accuracy of the cold junction sensor of the data acquisition module.

4 Estimation of Measurement Uncertainty

4.0 Uncertainty Estimation

The uncertainty estimation associated with the whole work is in three parts, (i) uncertainty associated with the calibration of the thermocouples with the existing data acquisition device in a climatic chamber, (ii) uncertainty associated with the calibration of the thermocouples with the new data acquisition module also in a climatic chamber, and finally (iii) uncertainty associated with temperature measurement with the new data acquisition module in a vacuum chamber. Further information on the above-listed uncertainty parts is presented in the following paragraphs.

4.1 Uncertainty of Calibration with USB-TEMP.

In order to estimate the uncertainty associated with the calibration of the thermocouples using the existing data acquisition device (USB-TEMP) influences introduced by the various input devices were considered. These input devices include the test thermocouple and data acquisition device for test thermocouple, reference thermometer, F100 precision thermometer, and the thermal source. As a result, the temperature of the hot junction of the test thermocouple is presented in the form of a model equation in equation 6.

$$T_X = T_{IS} + \partial T_{IS1} + \partial T_{IS2} + \partial T_R + \partial T_{OS} + \partial T_F + \partial T_D + \partial T_{RX} \qquad (6)$$

Where;

T_X is the temperature of the hot junction of the thermocouple.

T_{IS} is the measurement signal.

∂T_{IS1} is a correction due to the calibration of the thermocouple with a read-out device.

∂T_{IS2} is a correction due to the resolution of a readout device.

∂T_{OS} is a correction due to cold junction reference temperature.

∂T_R is a correction due to parasitic EMF.

∂T_F is temperature correction due to the non-uniformity of the equalization block.

∂T_{RX} Temperature correction due to the repeatability of temperature measurements.

In the vein, the combined uncertainty of the temperature of the hot junction of the test thermocouple is as shown in equation 7.

$$u_{c(tx)} = \sqrt{u_{res}^2 + u_{rep}^2 + u_p^2 + u_{cj}^2 + u_d^2 + u_{nu}^2 + u_a^2 + u_s^2 + u_{ref}^2 + u_{cal}^2 + u_{resd}^2} \qquad (7)$$

Where;

$u_{c(tx)}$ is the uncertainty associated with temperature measurement with USB-TEMP.

u_{res} is uncertainty due to the resolution of the readout device.

u_{rep} is the uncertainty due to the repeatability of temperature measurements.

u_p is the uncertainty due to parasitic EMF.

u_{cj} is the uncertainty due to cold junction accuracy of read out device.

u_d is the uncertainty due to the drift of reference thermometer.

u_{nu} is the uncertainty due to the non-uniformity of the equalization block.

u_a is the uncertainty due to the accuracy of F100.

u_s is the uncertainty due to the Stability of F100.

u_{ref} is the uncertainty due to the resolution of F100.

u_{cal} is the reference thermometer standard uncertainty.

u_{resd} is the uncertainty due to the linear approximation of correction function.

The repeatability of the temperature measurement was estimated by taking the temperature values at points (+150 °C, +20 °C, -40 °C). These points were chosen based on the maximum and minimum temperature, and at a point close to room temperature i.e. 20 °C. The repeatability of the temperature readings at each temperature point was estimated by calculating the standard deviation of repeated measurements using the existing data acquisition module with the equation 8 below [14].

$$s(x_k) = \sqrt{\frac{1}{N-1}\sum_{K=0}^{N}(x_k - \bar{x})^2} \qquad (8)$$

where:

$s(x_k)$ is the standard deviation of the measurement values,

x_k is the individual measurement values,

N is the number of measurements,

$\bar{x}$ is the mean of measurement values given by equation 9 [14].

$$\bar{x} = \frac{1}{N}\sum_{k=1}^{n} x_k \qquad (9)$$

where:

N is the number of measurements,

x_k are individual measurement values.

The repeatability of the temperature measurement with the existing data acquisition device is presented in Table 10 below.

Table 10: Repeatability with USB-TEMP

Calibration Points/ (°C)	**Repeatability/ (°C)**
+150	0.06
+20	0.03
-40	0.03

The highest repeatability value from the three temperature points was used in the uncertainty budget. The resolution of the data logger (USB-TEMP) was used to estimate the uncertainty due to the resolution in reading temperature values from the sensors and it is given as 24 bits [22]. The resolution of the USB-TEMP is converted to voltage using the equation 10 below [22].

$$LSB = \frac{Full - Scale\ Voltage\ Range}{2^N - 1} \qquad (10)$$

Where;

LSB is the least significant bit

N is the number of bits which is 24 bits in this case.

The full-Scale voltage range is given as 2.5 V.

The resolution of the USB-TEMP is therefore calculated as 0,298 µV while the uncertainty due to the cold junction accuracy of the USB-TEMP is ±0.5 °C [22]. The drift of the reference thermometer presented in the certificate is 0.003 °C [27]. The uncertainty due to the non-uniformity of the equalization block was calculated by measuring the temperature difference of two thermocouples on the same equalization block and the gradient is given as 0.18 °C. The accuracy, stability, and resolution of the F100 precision thermometer as in the manufacturer's instruction manual is ±0.02 °C, 0.005 °C/year and 0.001 °C respectively [24]. The uncertainty contribution due to parasitic EMF from previous calibration experience is given as 1.15 µV [16]. The sensitivity coefficient as taken from the reference table is given as 0.028 °C/µV [28]. The residual of the individual points in the calibration line fit was evaluated and the standard deviation of residual which is 0.081 °C was used as the uncertainty due to the linear approximation of correction function. Table 11 below shows the uncertainty budget for calibration with the existing method.

Table 11: Uncertainty budget for calibration with the existing method.

Quantity	**Symbol**	**Standard Uncertainty**	**Distribution**	**Sensitivity Coefficient**	**Uncertainty Contribution (°C)**
Resolution of read-out device	u_{res}	0.086 µV	Rectangular	0.028 °C/µV	0.019
Parasitic EMF	u_p	1.15 µV	Rectangular	0.028 °C/µV	0.025
Cold Junction	u_{cj}	0.29 °C	Rectangular	1	0.29
Non-uniformity of equalization block	u_{nu}	0.10 °C	Rectangular	1	0.10
Repeatability	u_{rep}	0.06 °C	Normal	1	0.06
Accuracy of F100	u_a	0.01 °C	Rectangular	1	0.01
Stability of F100	u_s	0.003 °C	Rectangular	1	0.003
Resolution of F100	u_{ref}	0.0006 °C	Rectangular	1	0.0006
The drift of reference PT-100	u_d	0.002 °C	Rectangular	1	0.002
Linear approximation of correction function	u_{resd}	0.081°C	Normal	1	0.081
Standard thermometer standard uncertainty *k=1*	u_{cal}	0.01 °C	Normal	1	0.01
Combined Uncertainty	u_c				0.33
Expanded uncertainty *k*=2	*U*				0.6

4.2 Uncertainty of Calibration with New Data Acquisition Device.

Estimation of the measurement uncertainty associated with the calibration of the thermocouples with the new data acquisition device is done as presented in section 4.1, but uncertainty contributions due to the existing data acquisition device are replaced with the uncertainty contributions due to the new data acquisition device. For the new data acquisition module, the temperature of the hot junction of the thermocouple is presented in the form of a model in equation 11 below.

$$T_X = T_{IS} + \partial T_{A1} + \partial T_{A2} + \partial T_V + \partial T_F + \partial T_{OS} + \partial T_R + \partial T_{RX} \qquad (11)$$

Where;

T_X is the temperature of the hot junction of the thermocouple.

T_{is} is the measurement signal.

∂T_{A1} is the correction due to the accuracy of the cold junction sensor.

∂T_V is the correction obtained from the reference voltage source.

∂T_F is the temperature due to the non-uniformity of the equalization block.

∂T_R is the correction due to the resolution of the DAQ.

∂T_{RX} is the correction due to the repeatability of the temperature measurements.

Again, the combined uncertainty due to the calibration with the new data acquisition device is presented in equation 12 below.

$$u_{c(new)} = \sqrt{u_a^2 + u_{res}^2 + u_{rep}^2 + u_{cal}^2 + u_{a2}^2 + u_s^2 + u_{res2}^2 + u_{resd}^2} \qquad (12)$$

Where;

u_a is the uncertainty due to the accuracy of the cold junction sensor.

u_{res} is the uncertainty due to the resolution of the hot junction device.

u_{rep} is the uncertainty due to the repeatability of the temperature measurement.

u_{cal} is the reference thermometer standard uncertainty.

u_{a2} is the uncertainty due to the accuracy of the F100.

u_s is the uncertainty due to the stability of the F100.

u_{resd} is the uncertainty due to the linear approximation of correction function.

u_{res2} is the uncertainty due to the resolution of the F100.

The repeatability of the temperature measurement was done as in the previous section for three temperature points and the result presented in Table 12.

Table 12: Repeatability for Calibration with new DAQ

Calibration Points/ (°C)	**Repeatability/ (°C)**
+150	0.08
+20	0.06
-40	0.07

The highest repeatability value for the temperature measurement is also used for the uncertainty estimation. The accuracy of the cold junction sensor ±1 °C while the resolution is given as 18 bits [26], [27]. The resolution is converted to voltage using equation 13 below [27].

$$LSB = \frac{2V_{REF}}{2^N} \tag{13}$$

Where;

LSB is the least significant digit.

V_{ref} is the reference voltage given as 2.048 V.

N is the number of bits which is 18 bits in this case.

As a result, the resolution of the new data acquisition module is calculated as 15.625 µV. The uncertainties associated with the reference PT-100 and F100 are the same as listed in section 4.1. Again, the uncertainty due to residual of individual point is estimated as 0.081 °C. Table 13 below shows the uncertainty budget for calibration with new DAQ.

Table 13: Uncertainty budget for calibration with new DAQ

Quantity	Symbol	Standard Uncertainty	Distribution	Sensitivity coefficient	Uncertainty Contribution/ °C
Accuracy of cold junction sensor	u_a	0.58 °C	Rectangular	1	0.58
Resolution of the data acquisition device	u_{res}	4.51 µV	Rectangular	0.028 °C/µV	0.13
Repeatability	u_{rep}	0.080 °C	Normal	1	0.08
Linear approximation of correction function	u_{resd}	0.081 °C	Normal	1	0.081
Standard thermometer standard uncertainty *k=1*	u_{cal}	0.010 °C	Normal	1	0.01
Accuracy of F100	u_{a2}	0.012 °C	Rectangular	1	0.012
Stability of F100	u_s	0.003 °C	Rectangular	1	0.003
Resolution of F100	u_{res2}	0.0006 °C	Rectangular	1	0.0006
Combined Uncertainty	$u_{c(new)}$				0.61
Expanded uncertainty *k*=2	U_c				1.2

4.3 Uncertainty Estimation for Temperature Measurement in Vacuum Chamber.

The temperature of the hot junction of the test thermocouple due to the measurement of temperature in the vacuum chamber is presented in the form of a model in equation 14 below.

$$T_X = T_{IS} + \partial T_{A1} + \partial T_{A2} + \partial T_V + \partial T_{OS} + \partial T_{RX} + \partial T_{RP} \tag{14}$$

Where;

T_X is the temperature of the Hot junction of the thermocouple.

T_{IS} is an indication of the new data acquisition module.

∂T_{A1} is the correction due to the accuracy of the cold junction sensor.

∂T_{A2} is the correction due to the resolution of the data acquisition device.

∂T_V is the correction obtained from the reference voltage source.

∂T_{Rx} is the correction due to the repeatability of the measurement.

∂T_{RP} is the correction due to the reproducibility of the temperature measurements.

Similarly, the model equation for the combined uncertainty of temperature measurement in a vacuum is as presented in equation 15 below.

$$u_c = \sqrt{u_{rp}^2 + u_{rep}^2 + u_a^2 + u_{res}^2 + u_{resd}^2 + u_{grad}^2 + u_{cal}^2 + u_{a2}^2 + u_s^2 + u_{res2}^2} \qquad (15)$$

Where;

u_a is the uncertainty due to the accuracy of the cold junction sensor.

u_{res} is the uncertainty due to the resolution of the new data acquisition device.

u_{resd} is the uncertainty due to the linear approximation of correction function.

u_{grad} is the uncertainty due to the temperature gradient between sensors.

u_{rep} is the uncertainty due to the repeatability of the measurement.

u_{rp} is the uncertainty due to the reproducibility of the measurement.

u_{cal} is the reference thermometer standard uncertainty.

u_{a2} is the uncertainty due to the accuracy of the F100.

u_s is the uncertainty due to the stability of the F100.

u_{res2} is the uncertainty due to the resolution of the F100.

The uncertainty due to the accuracy of the cold junction sensor is ±1 °C, while the resolution of the new data acquisition device as previously calculated according to equation 13 is 15.625 µV. The uncertainty due to the linear approximation of correction function was estimated by evaluating the residuals of individual calibration points and the standard deviation of residuals which is 0.084 °C was used. The temperature gradient (difference) between two closely mounted sensors (see figure 12) in a vacuum was evaluated and used to estimate the uncertainty due to temperature gradient. It is estimated by evaluating the difference between the temperature values measured from two closely mounted sensors and the average of the difference was calculated. The maximum value of 1.40 °C was also used.

4.3.1 Repeatability Evaluation in Vacuum.

To put the new data acquisition module to use in the vacuum, a relative measurement was carried out where 7 sensors were mounted on a plate made of anvil material which is turned such that it is facing the heat exchanger plate in the vacuum chamber with the sensors in between. As the new data acquisition module supports up to 16 channels, there is a need to confirm that the module can handle temperature measurement with all these channels. As such, all the 7 available thermocouples which are of the same type and model was used. This also helps to see how good or bad the temperature measurement data from the thermocouples match up. A dow corning vacuum grease with a very low outgassing possibility was used to improve the contact between the sensors and the heat exchanger in the vacuum chamber. Figure 12 below shows the sensor set up before the repeatability measurement was carried out.

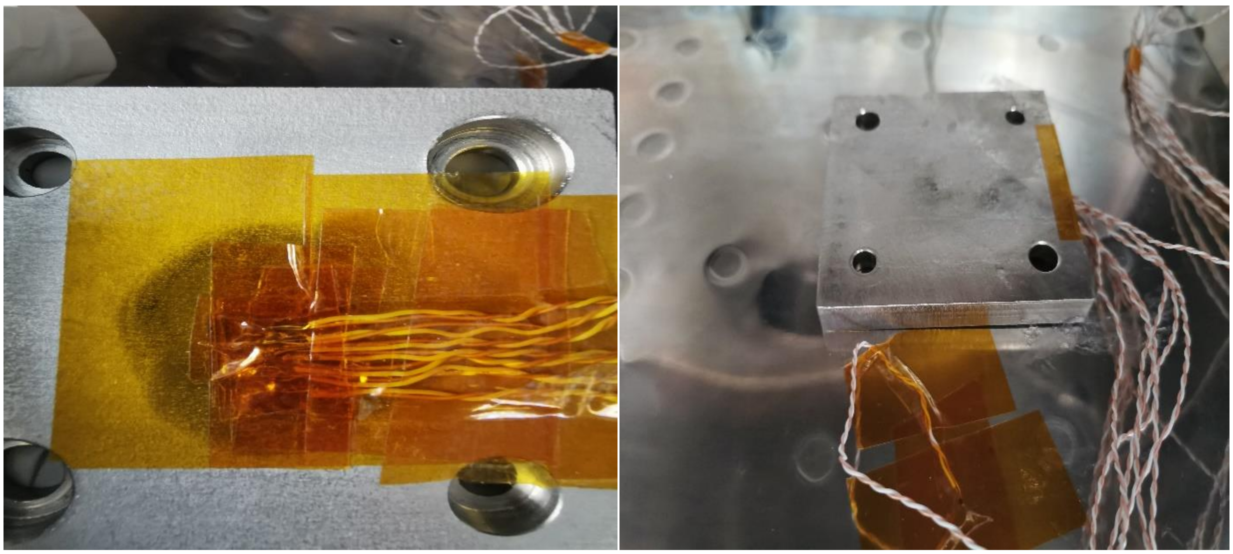


Figure 12: Sensor position before repeatability measurement.

In the picture, the sensors are kept closer together as much as possible to achieve spatial uniformity. The sensors are then connected to the data acquisition device, and temperature data was logged for a minimum of 5 hours after stabilization is achieved for three temperature points (+140, +20, and -40) °C as stabilization takes very long in a vacuum chamber. Again, the points were chosen based on the minimum, maximum, and the other point at room temperature. Three cycles of measurements were taken, and the standard deviation of the measurements was calculated using equation 7 to estimate the repeatability at each temperature point. The result is presented in Table 14 below.

Table 14: Thermocouple repeatability for each channel.

Thermocouple	Repeatability/ °C		
	+140 °C	+20 °C	-40 °C
T1	0.034	0.038	0.036
T2	0.033	0.038	0.035
T3	0.033	0.037	0.033
T4	0.030	0.039	0.034
T5	0.032	0.038	0.035
T6	0.033	0.036	0.035
T7	0.032	0.036	0.031

In comparing the repeatability in the vacuum chamber with that of the climatic chamber using the new data acquisition module, the repeatability value of the measurement in the climatic chamber is seen to be higher which implies that better repeatability value can be gotten in the vacuum chamber with the new DAQ. To evaluate the uncertainty due to repeatability here, the highest repeatability value in table 14 is used as a worst-case scenario.

4.3.2 Reproducibility

Reproducibility tests have been performed by the author over multiple days. The reproducibility test is important to evaluate how well the results logged with the new data acquisition module are reproducible when measurements are done at different times. Reproducibility conditions were mainly the same over the whole measurement pool - same instruments with the same setup, except that the measurement was recorded at different days and time. The reproducibility set up is the same as the set up in section 4.3.1 except that temperature values was logged from the thermocouples at five different points representing the high, medium, and low-temperature points to cover a wide measurement range of +140 °C, +80 °C, +20 °C, 0 °C and -40 °C for three different measurement cycles. The highest repeatability value from the three cycles is used in computing the reproducibility at each temperature point. Also, more data points are needed here in order to see how reproducible the temperature measurements are at points order than the ones chosen for repeatability measurement. The standard deviation of the data for thermocouple was calculated using equation 8 and the result is presented in Table 15 below.

Table 15: Reproducibility of Temperature Sensor in Vacuum.

Thermocouple	**Reproducibility / °C**				
	+140 °C	+80 °C	+20 °C	0 °C	-40 °C
T1	0.032	0.035	0.040	0.033	0.036
T2	0.035	0.033	0.032	0.034	0.038
T3	0.030	0.032	0.038	0.037	0.034
T4	0.033	0.035	0.035	0.033	0.035
T5	0.036	0.032	0.037	0.034	0.034
T6	0.033	0.035	0.038	0.034	0.036
T7	0.035	0.034	0.038	0.036	0.037

As done in the previous sections, the highest reproducibility value in table 15 above is used in the uncertainty calculation. The uncertainty budget for temperature measurement in a vacuum presented in Table 16 below.

Table 16: Uncertainty budget for temperature measurement in a vacuum.

Quantity	**Symbol**	**Standard Uncertainty**	**Distribution**	**Sensitivity coefficient**	**Uncertainty Contribution/ °C**
Accuracy of cold junction sensor	u_a	0.58 °C	Rectangular	1	0.58
Resolution of the data acquisition device	u_{res}	4.51 µV	Rectangular	0.028 °C/µV	0.13
Linear approximation of correction function	u_{resd}	0.084 °C	Rectangular	1	0.084
Gradient	u_{grad}	0.80 °C	Normal	1	0.80
Repeatability	u_{rep}	0.039 °C	Normal	1	0.039
Reproducibility	u_{rp}	0.04 °C	Normal	1	0.04
Standard thermometer standard uncertainty *k=1*	u_{cal}	0.010 °C	Normal	1	0.010
Accuracy of F100	u_{a2}	0.012 °C	Rectangular	1	0.012
Stability of F100	u_s	0.003 °C	Rectangular	1	0.003
Resolution of F100	u_{res2}	0.0006 °C	Rectangular	1	0.0006
Combined Uncertainty	u_c				1.00
Expanded uncertainty *k*=2	U				2.00

5 Conclusions

In this work, the temperature measurement system in a vacuum environment has been considerably improved. First, different temperature sensors were considered with ECSS standards in mind, and the thermocouple is deemed to be the most suitable temperature sensor for this task. After successfully selecting the suitable temperature sensor for vacuum application, the selected temperature sensor was calibrated using the existing measurement system available at the Tartu Observatory and it was discovered that the major source of uncertainty using this system is the soldered joint in the DB-50 adapter. Since this adapter is required for connecting the thermocouples inside the vacuum chamber to the data logging device (USB-TEMP) outside the vacuum chamber, for improved measurement results, an alternative method of data acquisition becomes necessary. As a result, a new data acquisition module that allows for data to be logged while being placed in a vacuum was made available to the author. While the new data acquisition gives better measurement results when used compared to the existing method, the accuracy of the data acquisition module can be further improved by ensuring that the influence due to the instability of the reference voltage source is estimated. Also, a more stable reference voltage source is recommended for future tests.

Finally, the measurement and uncertainty model were designed for the calibration of the thermocouples with the existing data acquisition device (USB-TEMP), new data acquisition device, and the temperature measurement with the new data acquisition device in a vacuum chamber. The expanded uncertainties were found to be 0.6 °C for calibration with existing method, 1.2 °C for calibration of thermocouples with new data acquisition module and 2.0 °C for temperature measurement in a vacuum, all at 95% percent confidence level, $k=2$ which matches with the uncertainty requirement for thermal vacuum testing.

References

[1] M. Ilarslan, Havacılık ve Uzay Teknolojileri Enstitüsu, IEEE Aerospace and Electronic Systems Society, IEEE Geoscience and Remote Sensing Society, and American Institute of Aeronautics and Astronautics, Eds., *2013 6th International Conference on Recent Advances in Space Technologies (RAST 2013): Istanbul, Turkey, 12 - 14 June 2013*. Piscataway, NJ: IEEE, 2013.

[2] R. S. S. Chisabas, G. Loureiro, and C. de O. Lino, "Space Thermal and Vacuum Environment Simulation," *Space Flight*, Jun. 2018, doi: 10.5772/intechopen.73154.

[3] X. Zhu, W. An, L. Chang, L. ZhenWei, and L. Zeyuan, "Research of digital temperature measurement system in vacuum thermal test based on DS18B20," *MATEC Web Conf.*, vol. 173, p. 03076, 2018, doi: 10.1051/matecconf/201817303076.

[4] S. Mwagomba, "A Method for Thermal Ambient Tests of Space Technology Equipment in a Thermal Chamber - Development and Validation," *Univ. Tartu*, 2014.

[5] *M. L. DONA, "Methods of Calibration and characterization of Temperature Controlled Environments," U.P.B. Sci. Bull., Series C, Vol.72, Iss. 2, 197-210, (2010).* .

[6] *European Cooperation for Space Standardization. ECSS-E-ST-10-03C, Space Engineering, Testing, 1 June 2012. Noordwijk, the Netherlands.* .

[7] R. S. S. Chisabas, G. Loureiro, C. de O. Lino, and D. F. Cantor, "Method for CubeSat Thermal-Vacuum Cycling Test Specification."

[8] W. F. Roeser and S. T. Lonberger, *Methods of Testing Thermocouples and Thermocouple Materials*. U.S. Department of Commerce, National Bureau of Standards, 1958.

[9] J. V. Nicholas and D. R. White, *Traceable Temperatures: An Introduction to Temperature Measurement and Calibration*, 2nd ed. Chichester ; New York: Wiley, 2001.

[10] S. Pilot and V. Naikan, "Reliability analysis of temperature sensor system," *Int. J. Reliab. Qual. Saf. Eng.*, vol. 20, Mar. 2013, doi: 10.1142/S0218539313500034.

[11] R. S. Figliola and D. E. Beasley, *Theory and design for mechanical measurements*, Seventh Edition. Hoboken, NJ: Wiley, 2019.

[12] D. Döring, P. Hein, and C. Spiessberger, "Temperature measurements in thermal-vacuum tests for spacecraft qualification – possibilities for infrared thermography," Jan. 2016, doi: 10.21611/qirt.2016.027.

[13] "BIPM, 'International vocabulary of metrology – Basic and general concepts and associated terms (VIM),' (2008)." .

[14] *Joint Committee for Guides in Metrology, JCGM 100:2008, "Evaluation of measurement data - guide to the expression of uncertainty in measurement," JCGM, (2008).* .

[15] J. C. Damasceno and P. R. G. Couto, "Methods for Evaluation of Measurement Uncertainty," *Metrology*, Nov. 2018, doi: 10.5772/intechopen.74873.

[16] *Guideline on calibration of thermocouple, EURAMET cg-8, Version 2.1 (10/11)*. .

[17] "SE000-Test Accuracy, Type K thermocouple Probe Data Sheet." Pico Technology.

[18] "SSU-MM Type T Thermocouple Sensor Data Sheet." Ellab Validation and Monitoring Solutions.

[19] Labfacility Temperature and Process Technology, "XF-1230-FAR-Thermocouple Data Sheet." .

[20] *Installation and Operation manual, Simpati software Version 4.06, (2011).* .

[21] *Weiss Technik, Temperature and Climatic Test Chambers, Greizer, Germany, (2010).* .

[22] *Measurement Computing Corporation (MCC), USB Temp Multi-sensor Temperature Measurement User guide, rev 13, Massachusetts, USA (2014).* .

[23] "T100-Series Reference Thermometer Specification." Isotech North America.
[24] *Automatic Systems Laboratories (ASL), F100 Precision thermometer user manual, Brentwood, N. America, (2011). .*
[25] Box and Jenkins, 1976, *NIST/SEMATECH e-Handbook of Statistical Methods, http://www.itl.nist.gov/div898/handbook/, 2012. .*
[26] Microchip Technology Inc., "MCP 9800/1/2/3, 2-Wire High-Accuracy Temperature Sensor Data Sheet." 2010.
[27] Microchip Technology Inc., "MCP 3422/3/4, 18-Bit, Multi-channel Analog-to-Digital Converter with I2C Interface and Onboard Reference Data Sheet." 2009.
[28] L. P. Robert *et al.*, *Thermocouple Reference Tables Based on the IPTS-68*. Washington D.C: National Bureau of Standards, 1974.

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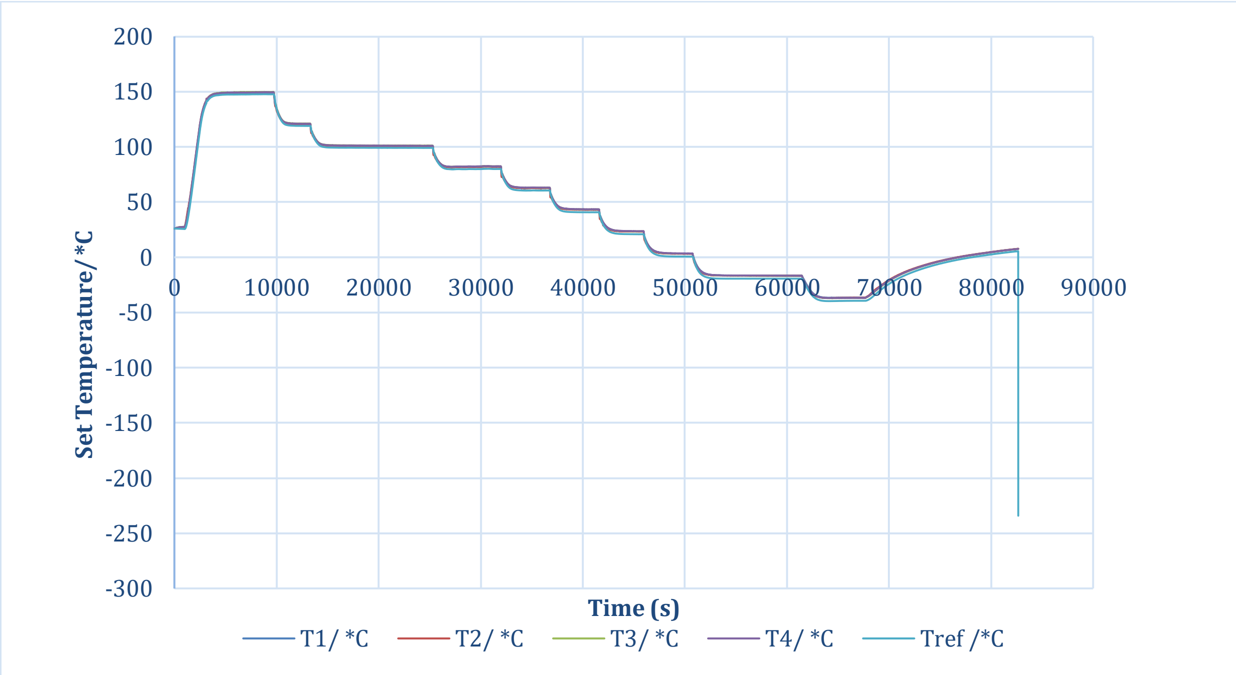
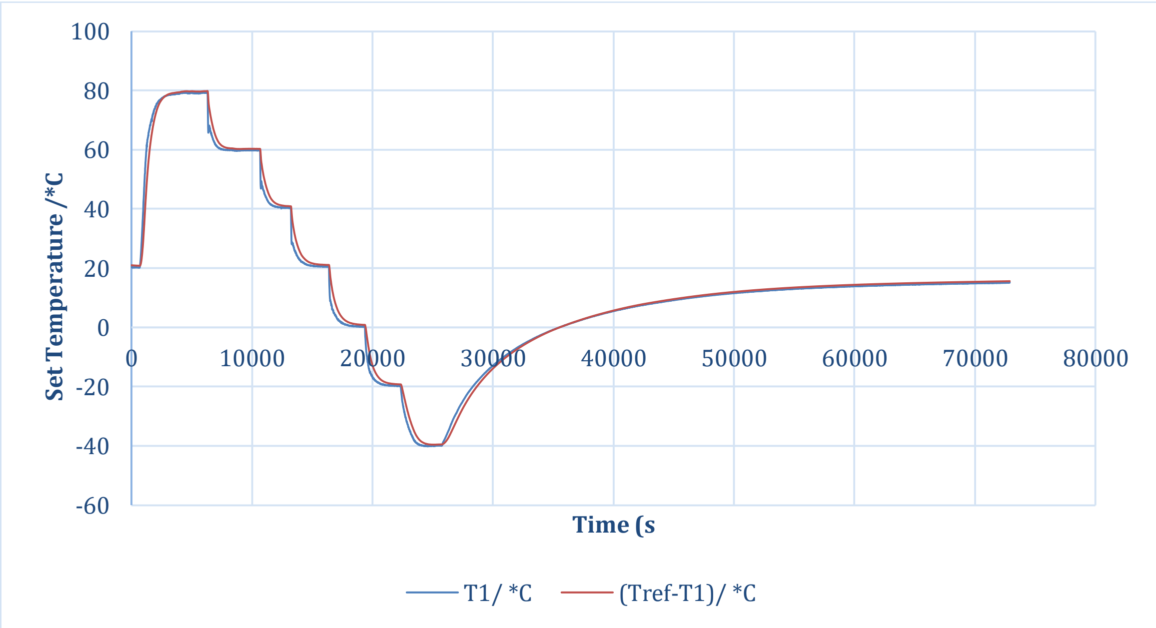
Appendices

Appendix 1: Dwell Time for Calibration with USB-TEMP.



Appendix 2: Dwell Time for Calibration with Direct Connection to Data Logger.



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INFORMATION SHEET

Information sheet for Akintola Adeyinka Jimoh's Master's thesis (2020) "Characterization of a Temperature Measurement System for Use in Vacuum" ***Infoleht**. Akintola Adeyinka Jimoh Magistritöö (2020)* "Temperatuuri mõõtmise süsteemi iseloomustamine vaakumis kasutamiseks"
Keywords: Thermal Vacuum Testing. Temperature Measurement, Measurement Uncertainty, Vacuum Chamber. ***Märksõnad:*** Termovaakumkatsetused, Temperatuurimõõtmised, Mõõtemääramatus, Vaakumkamber
Summary: Thermal vacuum tests must be performed to ensure the survivability of the spacecraft during the development and performance validation stages. To carry out these tests, vacuum compatible temperature sensors are placed on different sub-systems of a spacecraft in a vacuum chamber. For the reliability of this test, the temperature sensors to be used need to be calibrated. This work, therefore, aims at improving the temperature measurement system currently used for thermal vacuum testing at the Tartu Observatory, University of Tartu. A suitable vacuum compatible sensor was selected and calibrated in the climatic chamber using the existing measurement system available at the observatory and a new measurement system introduced in this work. Both measurement systems were characterized, and measurement and uncertainty models were designed and estimated for the measurements carried out both in the climatic chamber and in the vacuum chamber. ***Lühikkokuvõte:*** Termovaakumkatsetused on vajalikud, et kindlustada satelliidi vastupidavus vaakumile. Katsetel kinnitatakse vaakumis kasutatavad temperatuuriandurid vaakumkambrisse asetatud satelliidi alamsüsteemide külge. Katsetulemuste usaldusväärsuse tagamiseks peavad temperatuuriandurid olema kalibreeritud. Käesoleva töö eesmärgiks on parandada olemasolevat temperatuurimõõtmise süsteemi, mida Tartu Ülikooli Tartu observatooriumis vaakumkatsetuste läbiviimiseks kasutatakse. Katsete jaoks valitakse välja sobiv temperatuuriandur, mis kliimakambris kahe erineva süsteemiga kalibreeritakse. Kalibreerimisel kasutatatakse nii olemasolevat temperatuuri mõõtmise süsteemi kui ka uut temperatuuri mõõtmise süsteemi, mida käesolevas töös tutvustatakse. Mõlema mõõtmissüsteemi jaoks koostatakse mõõtemudel ning määramatuse mudel, et hinnata kliimakambris ja vaakumkambris teostatavate temperatuurimõõtmiste määramatust.