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Calibration and in site commissioning of the CMS ipipe3 FBG sensors

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Abstract

My Summer Student project was framed in the LS2 CMS iPipe upgrade. My responsibility was to compute the calibration and recalibration coefficients for all of the sensors mounted on the CMS Central Beam Pipe. I calibrated and recalibrated the FBG-based monitoring system meant to detect temperature fluctuations on the CMS central BP, the Endcap, and the HF-CT2. The findings gave us the calibration equation for each of the ipipe3's 90 FBGs, demonstrating the Fiber Bragg Grating sensors' reliability and sensitivity. We may deduce that recalibration is required after installation to account for mechanical impact of this process, as well as during bakeout to account for changes induced by thermal elongation caused by the exposure to high temperatures. Finally, following the calibration and recalibration procedure, we see that all sensors are fully functioning and ready for data collection following the LS2.

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1 Fiber Bragg Grating

A fiber optic sensor's job is to alter the characteristics of a propagating light wave in response to the factor being monitored in the environment. Fiber Bragg grating is composed of a periodic modulation of the refractive index in the optical fiber core. When light is passing along the fiber's core, a certain amount of it is reflected depending on the index variation, and these reflections are called the Bragg wavelengths while the remainder of the light spectrum is transmitted through the FBG as shown in (Figure 1).

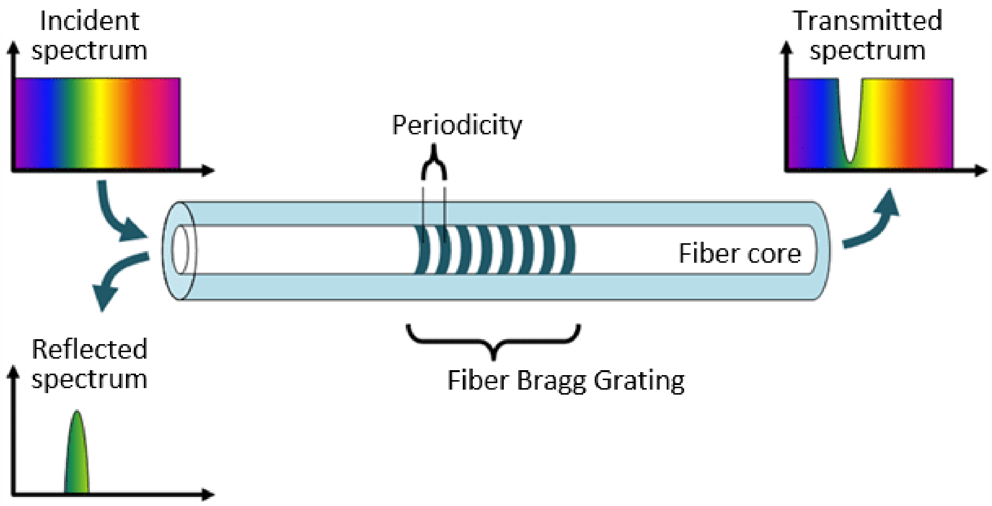


Figure 1: Incident and Reflected Spectrum on the FBG

These Wavelengths are defined according to the following equation:

$$\lambda_{Bragg} = 2 * n_{eff} * \Lambda$$

With λ_{Bragg}: being the Bragg Wavelength, n_{eff}: effective refractive index, and Λ: Grating pitch.

First discovered by Hill et al. in 1978, gratings were not commercially used until the mid-1990s. Fueled by communications requirements and the ramping up of the telecommunications bubble, a massive increase in the number of organizations and research groups involved in the design, production, packaging, and implementation of gratings occurred. Many industry participants made a substantial transition from communications to sensing applications shortly after the telecoms bubble burst. At the time, continuing to use the technological and production infrastructure was a sensible and strategic decision on the part of FBG producers. The majority of sensing applications concentrated on discrete, single-point sensing of certain parameters, such as strain and temperature, utilizing sensors based on embedded or packaged gratings.

In an FBG sensor, both the effective refractive index and the grating pitch are affected by external factors such as strain and temperature. These changes lead to a variation in the Bragg wavelength making FBGs very good intrinsic sensors. When the FBG is subjected to a force F, the signal changes according to the following formula:

$$\frac{\Delta\lambda_{bragg}}{\lambda_0} = (1 + \frac{1}{n_{eff}}\frac{\delta n_{eff}}{\delta S})(\frac{\delta\Lambda}{\Lambda * \delta F})\Delta F$$

With S: strain. It is usually estimated that the sensitivity of an FBG to an axial strain is 1 nm/millistrain, for a grating of 1300 nm.

In addition, if a variation in the temperature ΔT occurs, the Bragg wavelength of the FBG will vary according to the following equation:

$$\frac{\Delta\lambda_{bragg}}{\lambda_0} = \frac{1}{n_{eff}}\left(\frac{\delta n_{eff}}{\delta T}\right)\Delta T + (\frac{\delta\Lambda}{\Lambda * \delta T})\Delta T$$

Due to the thermo-optic effect, it is estimated that the temperature coefficient is about 0.01nm/˚C, for a grating of 1550 nm. It is also affected by the thickness and material of the fiber coating. By increasing the coating thickness, the saturating trend increases.

Moreover, if the FBG is affected by both strain and temperature consequently, the Bragg wavelength shift can be expressed as:

$$\frac{\Delta\lambda_{bragg}}{\lambda_0} = (1 - P_e) * S + \left((1 - P_e) * \alpha + \xi\right) * \Delta T$$

Where P_e is the photo-elastic constant, α is the thermal expansion coefficient, and ξ is the thermo-optic coefficient. However, if the FBG is affected by both strain and temperature it is not possible to measure the strain occurring on the sensor. To do so, it is required to install another similar FBG that is only affected by the temperature change near the one used for strain measurement, and then compensate the change in Bragg wavelength occurring from temperature change from the one obtained by the strain sensor using the following formula:

$$\Delta\lambda_{Bragg} = \Delta\lambda_{Temperature} + \Delta\lambda_{Strain}$$

Many features make FBG sensors better than traditional sensors (strain gauge, thermocouple). The first one being, the minimal space needed to install FBGs compared to other sensors, a single fiber that can contain up to 100 sensors requires only 1 cable, while each thermocouple or strain gauge requires its own cable. In addition, unlike other sensors, FBGs are not affected by electromagnetic forces making them a perfect fit for projects where huge electromagnetic forces are available.

2 FBG Monitoring Systems for CMS

The European Organization for Nuclear Research (CERN) is the world's largest experimental facility for scientific research, with some of the most complex scientific instruments, including particle accelerators, conducted to understand the constituents of matter and their interactions, and provide insights into crucial laws of nature. The Large Hadron Collider (LHC) includes four large particle physics detectors deployed around its 27-kilometer perimeter, including the Compact Muon Solenoid (CMS), ATLAS, LHCb, and ALICE each used for a certain research purpose. The CMS, located in a subterranean cavern near the French town of Cessy, was built to analyze a wide range of physical events, from the completion of Standard Model predictions in search of the Higgs Boson to the investigation for novel physics outside the Standard Model at the TeV scale.

Since 2009, many FBG based monitoring systems were installed in the underground site of CMS. During the 3 years of LHC Run1 200 temperature and strain FBGs were installed. During the Long Shut-Down 1 (LS1) period that started from February 2013, the FBG monitoring system was expanded. Covering the whole CMS experiment, from the outside and the inside, almost one thousand FBG sensors were installed and operational.

The first FBG Monitoring System was installed on the tracker Bulkhead external surface. This monitoring system consisted of 2 arrays of 10 FBG sensors each. The sensors were embedded in a ceramic material and each sensor was located 2 meters away from the other. This system was used to measure the temperature of the two bulkhead sides (positive and negative) as shown in Figure 2, and it did so continuously throughout the year 2011 until the start of the LS1.

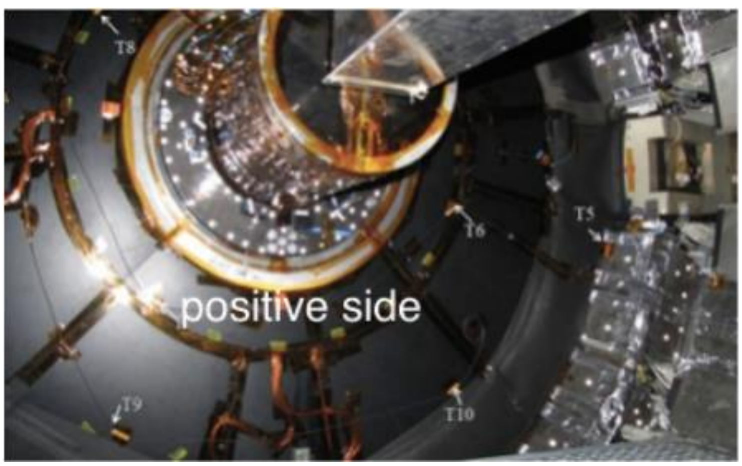


Figure 2: Bulkhead FBG Monitoring System on The Positive Side

Another FBG Monitoring system is installed on the HF riser structure. It includes eleven FBG sensors, where ten of them are glued to the structure to measure the strain deformation caused by the magnet cycles on the detector structure. The eleventh sensor is left free to measure the temperature changes without being affected by the strain, it is used as thermal compensator to the strain sensors. Similarly, an FBG monitoring system was installed to monitor the temperature of the whole CMS Experimental Underground Cavern (UXC). It includes a 2 km long SMF-28 fiber with sixty FBG sensors (Figure 3). In addition, FBGs are used in various other monitoring

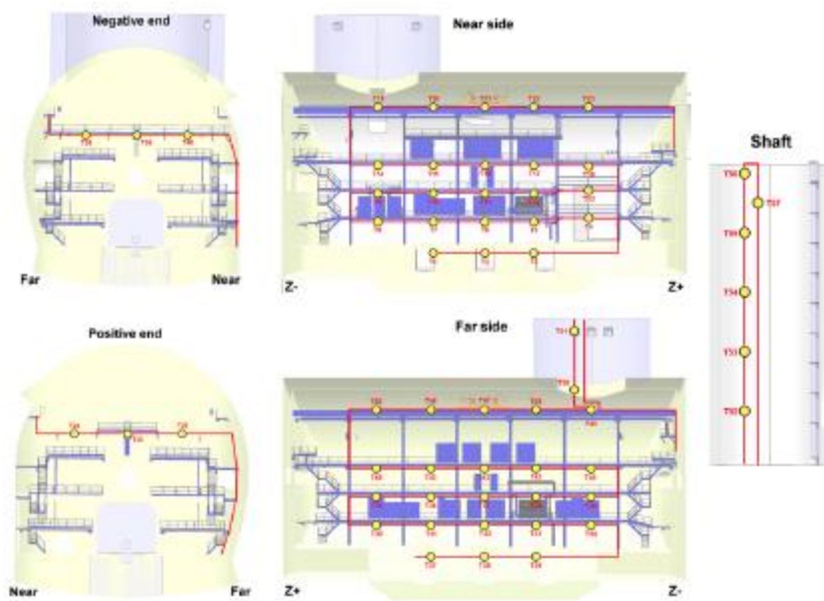


Figure 3: FBG Monitoring System installed in the CMS Cavern.

systems such as the Beam Radiation Monitoring temperature monitoring system (80 Temperature Sensors), the External Yoke strain monitoring system (10 Temperature sensors and 25 Strain sensors), and the tracker RH monitoring system, which is composed of 72 fiber optic sensors, each of these fibers is composed by a FBG temperature sensor and a FBG relative humidity sensor. Finally, the Central Beam pipe monitoring system also known as the iPipe is the FBG based monitoring system that will be further discussed in this report, explaining the calibration and recalibration process of its sensors before and after the.

3 CMS Beam Pipe Monitoring System

3.1 iPipe1 Monitoring System

The Central Beam Pipe is an important part of the CMS experiment and the LHC, it is the point where the high energy proton-proton collisions occur. During the LHC LS1 period, the new central BP was placed. It consists of a 3-meter-long Beryllium tubular section with an inner diameter of 45mm and a thickness of 0.8mm. This Beryllium section is sealed on both sides with two conical aluminum (Al EN AW-2219) sections, each one of them has a length of 1.5 m and an external diameter of 65mm. (Figure 4)

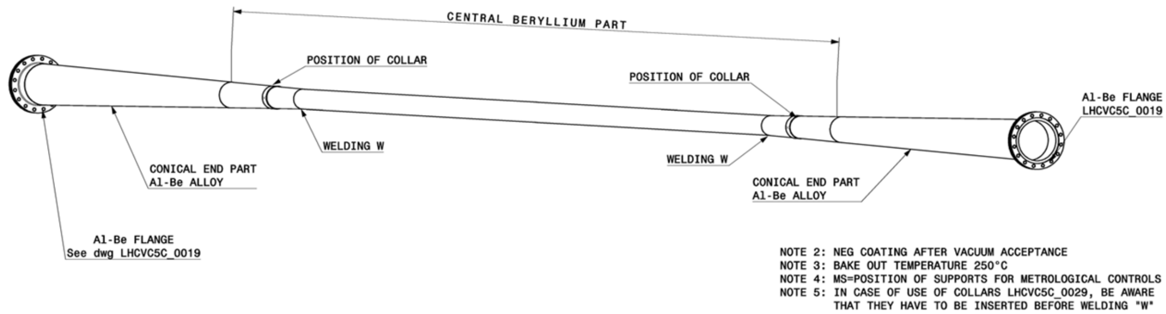


Figure 4: CMS Central Beam Pipe

The CMS central BP is only one section of the Beam Pipe System. It also includes an Endcap and HF-CT2 on each side of the Central Beam Pipe (Figure 5).

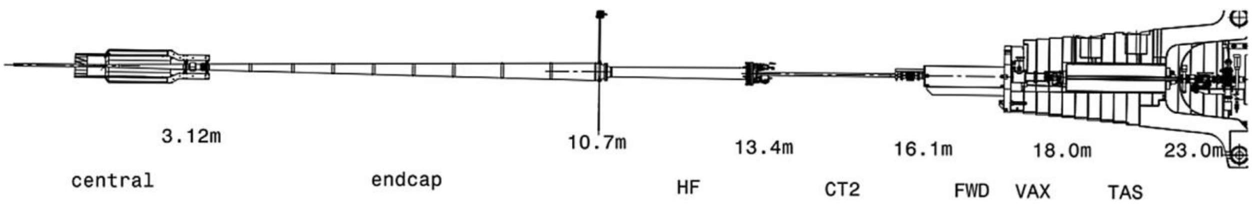


Figure 5: CMS Complete Beam Pipe

It has to withstand extreme vacuum conditions (up to 10^{-13} atm) without interfering with the particles resulting from the collisions. That is the reason why the beryllium tube needs to be constantly monitored, making sure of its structural health and condition. In order to do so, a monitoring system based on Fiber Bragg Grating (FBG) sensors called iPipe monitoring system was designed and installed by the CMS team during the LS1. This monitoring system does not impact the particle detectors wrapped around the pipe; it is immune to radiation which is one of the most important specifications required in a High Energy Physics environment, in addition to low complexity layout, multiplexing, and the ability to measure multiple parameters.

The iPipe 1 was installed only on the Central Beam Pipe and a small sector of the Endcap and the HF. It is made up of four naked glass SMF-28 fibers that are positioned longitudinally along the Beam Pipe's cardinal locations as shown in (Figure 6).

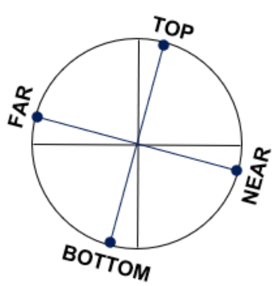


Figure 6: Location of Sensor Arrays on the Central BP

Each one of these fibers is an array of 16 FBG sensors with 7 of them glued on the BP in order to get affected by the deformation of the BP and used as strain measuring sensors, while the remaining 9 FBGs are left unglued and in contact with the BP to be used as thermometers and thermal compensators for the strain sensors without being affected by the strain occurring in the BP. Figure 7 shows a schematic representation of the sensor's distribution on the BP, showing the positioning of the strain and temperature sensors too. After installing the sensors, during the bakeout due to the thermal expansion of the beam pipe and the glue dots holding the fiber, the arrays faced an abnormal mechanical tension leading to the breaking of the fiber arrays. After reparation, only 40 out of 64 FBGs were reliable and used to gather temperature and strain measurements.

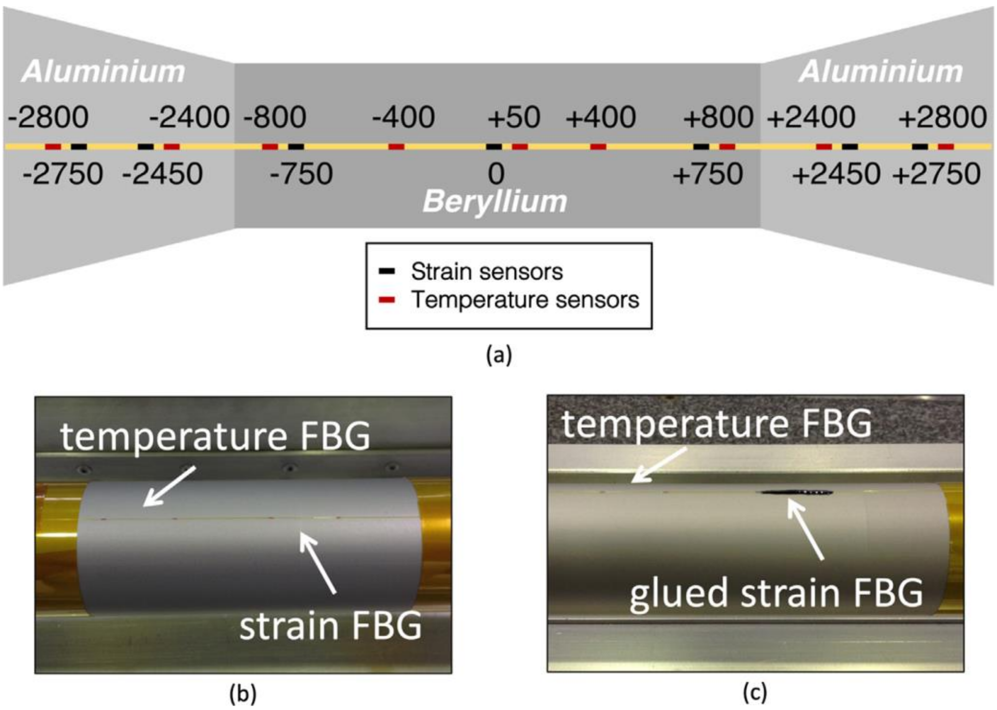


Figure 7: Representation of the sensors on the BP and presentation of temperature and glued strain sensors

3.2 iPipe3 Monitoring System

During the LS2 when all machines are turned off to allow technical upgrades and maintenance. During this shutdown, the CMS Beam Pipe was replaced with a completely new one. A new monitoring system was installed, and it is called iPipe3. Similar to iPipe1, iPipe3 is also based on FBG sensors. However, the new monitoring system was not only installed on the central beam pipe, but it is also extended to the Endcap, and the HF-CT2. Unlike the previous monitoring system, iPipe3 only contains FBG temperature sensors, they are installed on the Central Beampipe, Endcap Pipe, and the HF-CT2 pipe. For the central beampipe, 2 bare fiber arrays with pure silica core are installed, each containing 11 FBG sensors spaced by 0.5 meters starting from the IP (Figure 8).

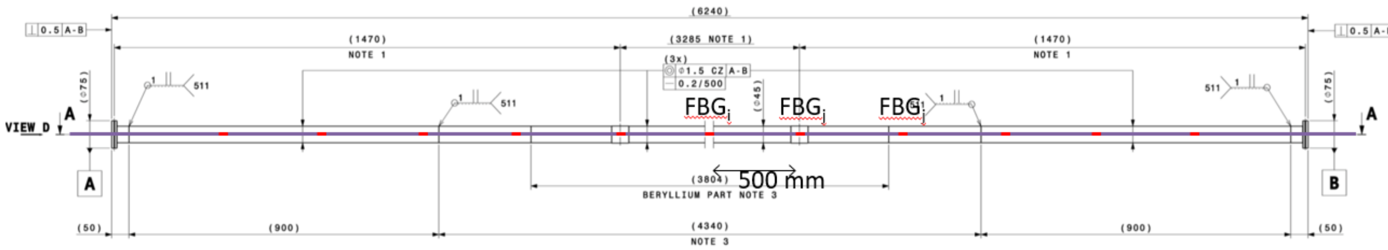


Figure 8: Central Beampipe Sensors placement.

Regarding the Endcap pipes, 2 fiber arrays are installed on each pipe. Each array contains 8 FBG sensors spaced by 0.82 meters (on average). The fibers are inserted in a stainless-steel capillary with an outer diameter of 1.6mm to handle bakeout constraints (Figure 9).

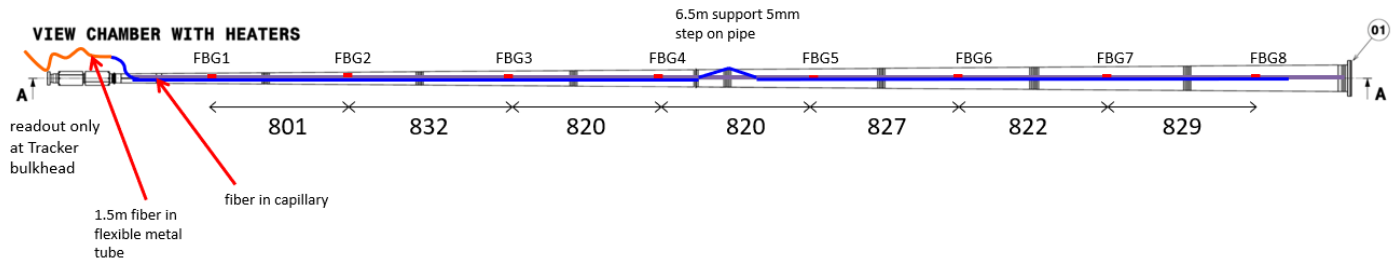


Figure 9: Endcap Sensors Placement

Regarding the HF-CT2 pipes, 2 fiber arrays are installed on each pipe. Each array contains 9 FBG sensors with the spacing shown in (Figure 10). The fibers are also inserted in a stainless-steel capillary with an outer diameter of 1.6mm to handle bakeout constraints.

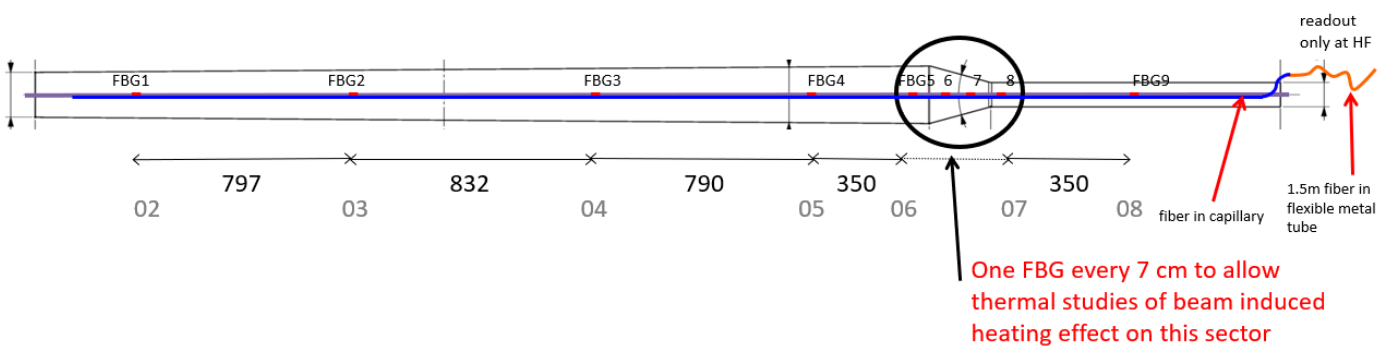


Figure 10: HF-CT2 Sensors Placement

3.3 Bakeout of CMS Beam Pipe

After installing the ipipe in the CMS detector, the bakeout procedure was executed. During the bakeout, the Beam Pipe was exposed to nominal vacuum level and an external temperature of 200 ˚C. The purpose of exposing the Beam Pipe to such harsh conditions is to secure the removal of all residual gas molecules attached to its internal walls. The bakeout is only done on the endcap and the HF-CT2, that’s why, to protect the fibers from being damaged during the wrapping and the bakeout, they are installed in a 1.6mm diameter stainless steel capillary tube as seen in Figure 11.

Figure 11: HF-CT2 Fiber Inside Capillary Tube

3.3.1 HF-CT2 #2

As shown in Figure 11, for the HF-CT2 the sensors are installed above the first Kapton layer, there is only one Kapton layer between the capillary and the beampipe. Two arrays of 9 FBGs are installed on the sides Figure 12 with the first being in contact with the beampipe at the short conical part and follows the gap at the long conical part Figure 13 and the second follows the gap at the long conical part only.

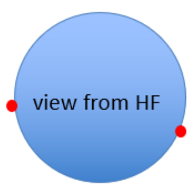


Figure 12: Location of Sensor Arrays on the HF-CT2

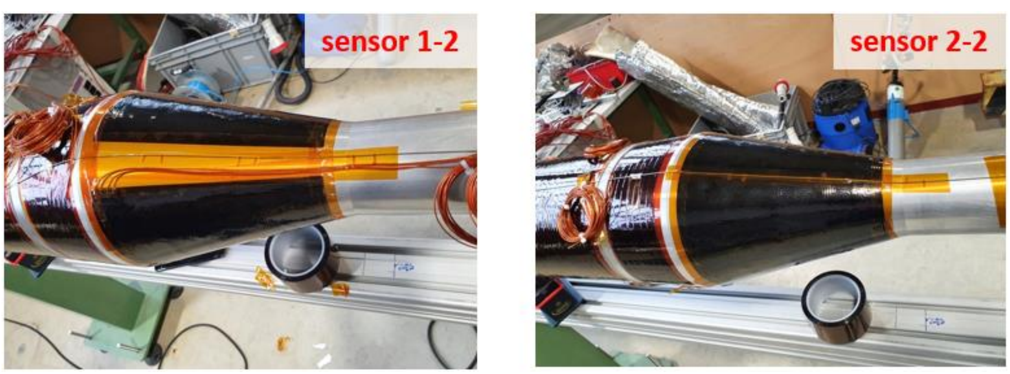


Figure 13: Fiber Arrays on the HF-CT2

In addition, four PT1000 temperature sensors were installed to measure the temperature in four different positions on the HF-CT2 prior to the bakeout Figure 14.

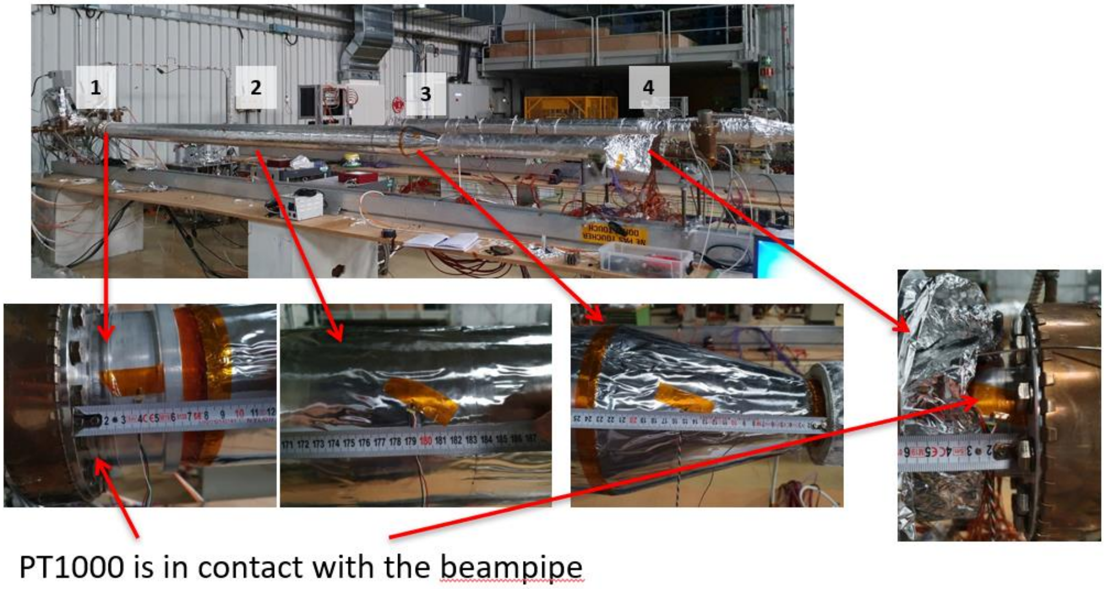


Figure 14: PT1000 Sensors on HF-CT2 before bakeout

3.3.2 Endcap

Similar to the HF-CT2, sensors are installed above the first Kapton layer on the Endcap. Two arrays of 8 sensors each are installed on each Endcap Figure 15. The first array (Sensor 3-1 and 3-2) follows the gap of the heating pads all along the pipe, the second array (Sensor 4-1 and 4-2) follows the gap of the heating pads only at FBG 6 7 and 8 while FBGs 1 to 5 are above the heating pads because one pad wraps the pipe in these areas Figure 16.

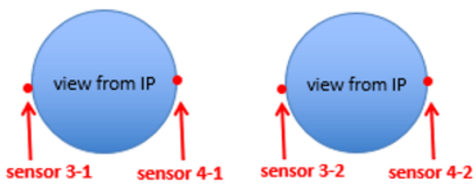


Figure 15: Location of Sensor Arrays on Encaps 1 and 2

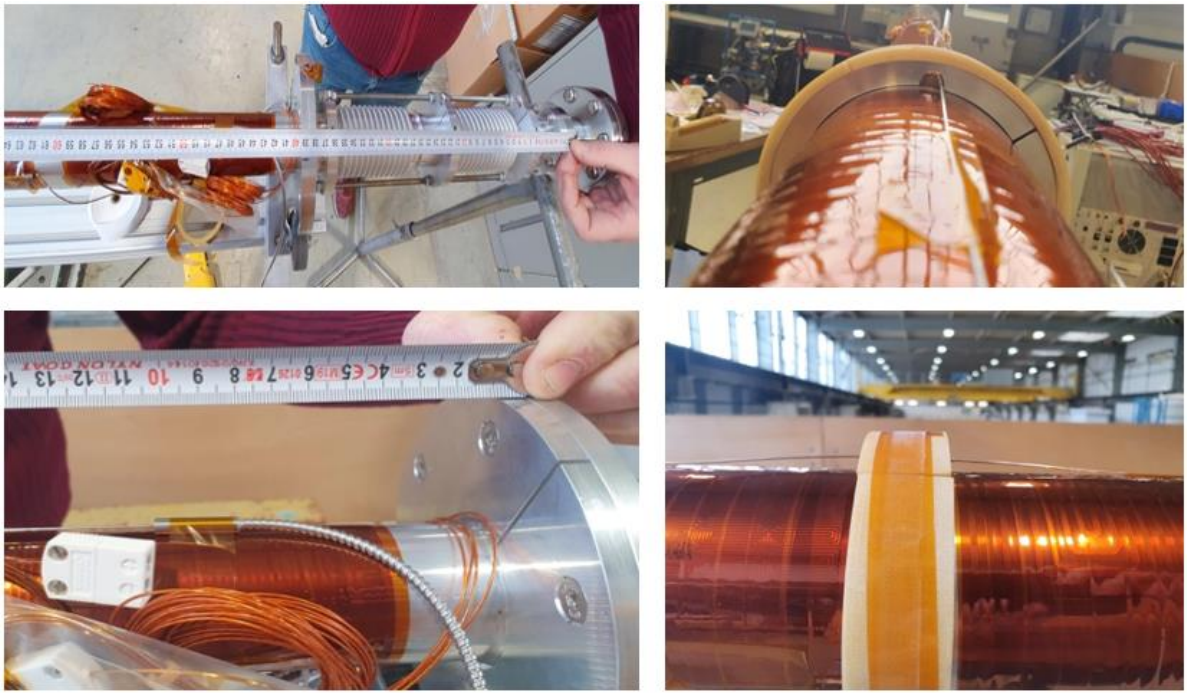


Figure 16: Fiber Arrays on the Endcap 1

In addition, five PT1000 temperature sensors were installed on each endcap to measure the temperature in five different positions on the Endcap after the bakeout(Figure 17 Figure 18).

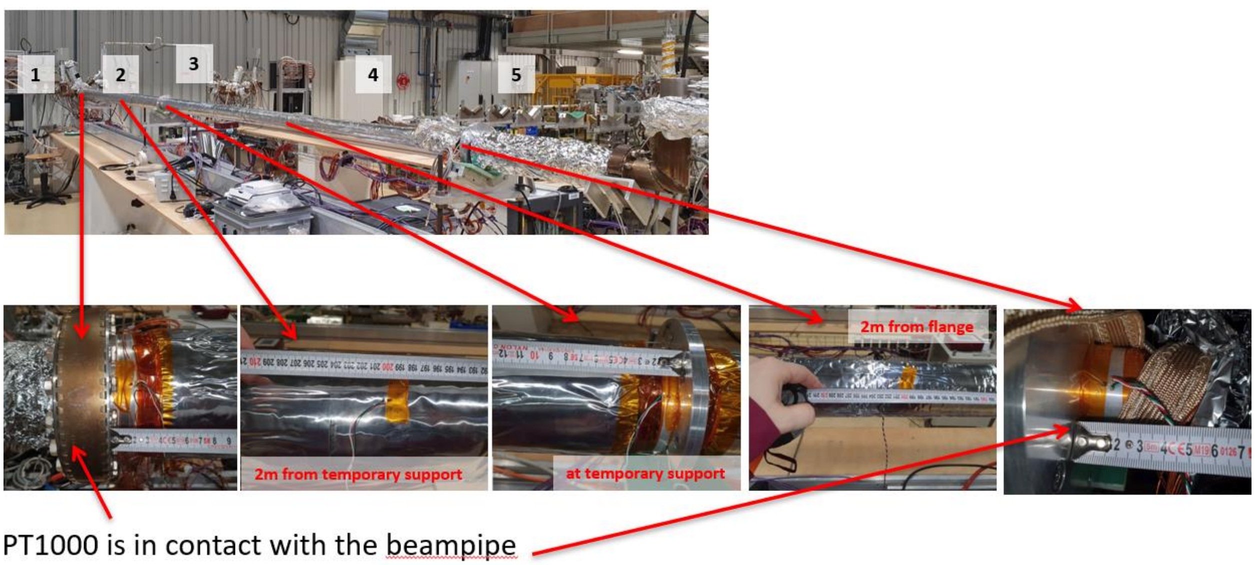


Figure 17: PT1000 Sensors on Endcap 1 after bakeout

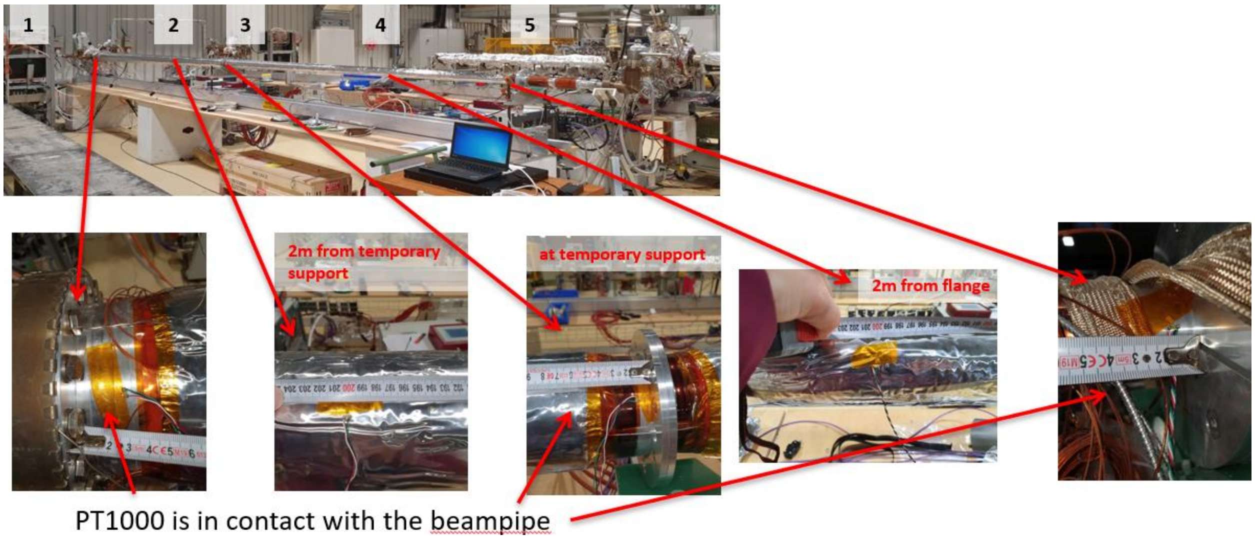


Figure 18: PT1000 Sensors on Endcap 2 after bakeout

4 Objective:

The objective of this report is to show a detailed explanation of the calibration process of the Endcap and HF-CT2 sensors, and the recalibration process of the Central Beampipe sensors, in addition to the recalibration process and data acquisition during the bakeout.

5 Calibration:

The calibration and data acquisition were done at CERN in the climatic chamber where sensors were placed as shown in Figure 19. In this figure we can see the way sensors are wrapped in the climatic chamber with a PT1000 Sensors (blue colored) on each FBG.

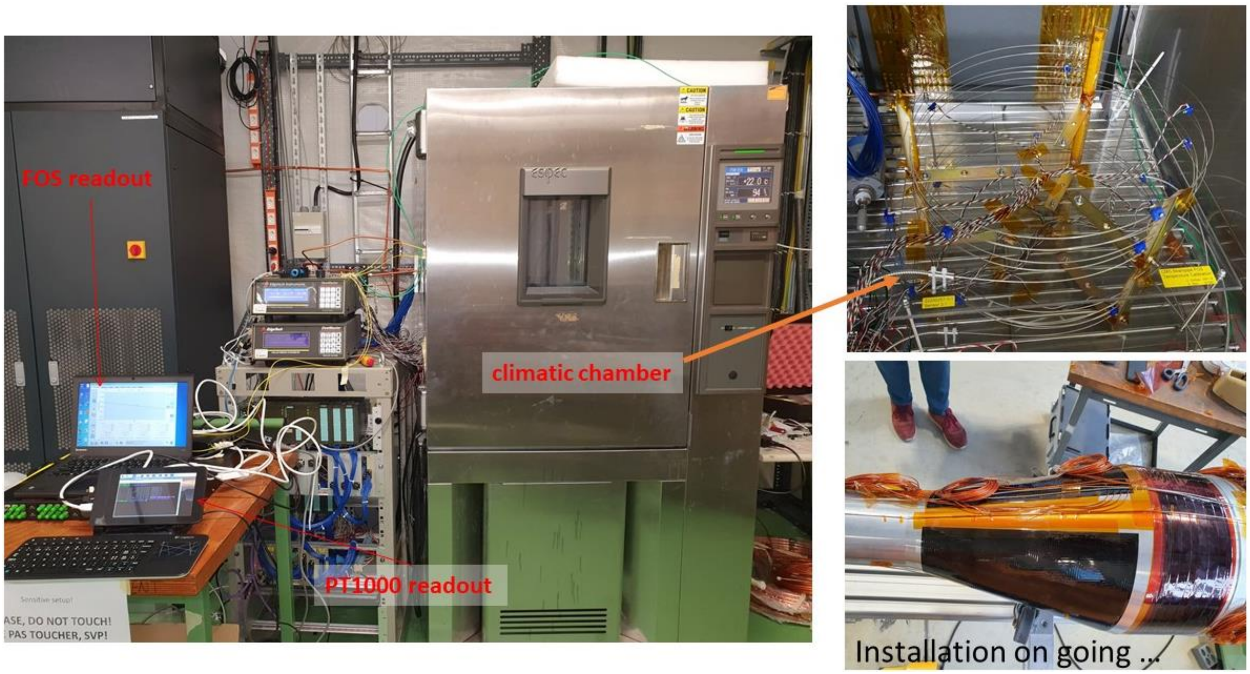


Figure 19: Climatic Chamber and Placement of Sensors

First, using a code written on MATLAB, the data acquired was filtered, taking only steady state temperature and wavelength values. Next, the steady state data were used to calculate the calibration constants P1 and P2 for each of the sensors with:

$\lambda(nm) = P1 * T(°\text{C}) + P2.$

Then, the maximum and minimum deviation were obtained, as shown in Table 1. Finally, all necessary data were plotted. Note that plots for all sensors are available in the appendix below.

FBG	P1	P2	Max Deviation (nm)	Min Deviation (nm)
EndCap_31_1	0.011	1529.880	0.032	-0.028
EndCap_31_2	0.011	1534.908	0.008	-0.007
EndCap_31_3	0.011	1539.868	0.008	-0.006
EndCap_31_4	0.011	1544.847	0.008	-0.006
EndCap_31_5	0.011	1549.882	0.008	-0.005
EndCap_31_6	0.011	1554.854	0.006	-0.006
EndCap_31_7	0.011	1559.850	0.008	-0.006
EndCap_31_8	0.011	1564.756	0.008	-0.006
EndCap_41_1	0.011	1527.331	0.031	-0.029
EndCap_41_2	0.011	1532.353	0.008	-0.007
EndCap_41_3	0.011	1537.319	0.008	-0.007
EndCap_41_4	0.011	1542.301	0.009	-0.006
EndCap_41_5	0.011	1547.290	0.006	-0.006
EndCap_41_6	0.011	1552.280	0.006	-0.006
EndCap_41_7	0.011	1557.269	0.008	-0.006
EndCap_41_8	0.011	1562.279	0.008	-0.006
EndCap_32_1	0.011	1530.017	0.031	-0.026
EndCap_32_2	0.011	1535.024	0.008	-0.008
EndCap_32_3	0.011	1540.020	0.007	-0.006
EndCap_32_4	0.011	1545.013	0.007	-0.007
EndCap_32_5	0.011	1549.985	0.008	-0.006
EndCap_32_6	0.011	1554.978	0.007	-0.006
EndCap_32_7	0.011	1559.965	0.008	-0.006
EndCap_32_8	0.011	1564.976	0.007	-0.005
EndCap_42_1	0.011	1527.224	0.007	-0.005
EndCap_42_2	0.011	1532.267	0.007	-0.006
EndCap_42_3	0.011	1537.254	0.008	-0.006
EndCap_42_4	0.011	1542.268	0.008	-0.006
EndCap_42_5	0.011	1547.399	0.007	-0.007
EndCap_42_6	0.011	1552.236	0.007	-0.005
EndCap_42_7	0.011	1557.193	0.007	-0.005
EndCap_42_8	0.011	1562.230	0.007	-0.006

Table 1: Endcap Sensors Calibration Data

FBG	P1	P2	Max Deviation (nm)	Min Deviation (nm)
HF-CT2_11_1	0.011	1529.804	0.013	-0.010
HF-CT2_11_2	0.011	1534.800	0.009	-0.008
HF-CT2_11_3	0.011	1539.796	0.010	-0.007
HF-CT2_11_4	0.011	1544.813	0.011	-0.008
HF-CT2_11_5	0.011	1549.782	0.011	-0.008
HF-CT2_11_6	0.012	1554.794	0.012	-0.008
HF-CT2_11_7	0.012	1559.760	0.011	-0.008
HF-CT2_11_8	0.012	1564.744	0.010	-0.008
HF-CT2_11_9	0.012	1569.712	0.007	-0.005
HF-CT2_12_1	0.011	1529.815	0.013	-0.009
HF-CT2_12_2	0.011	1534.804	0.010	-0.007
HF-CT2_12_3	0.011	1539.810	0.009	-0.006
HF-CT2_12_4	0.011	1544.786	0.010	-0.007
HF-CT2_12_5	0.011	1549.772	0.010	-0.007
HF-CT2_12_6	0.011	1554.772	0.011	-0.007
HF-CT2_12_7	0.012	1559.738	0.010	-0.006
HF-CT2_12_8	0.012	1564.744	0.010	-0.007
HF-CT2_12_9	0.012	1569.740	0.007	-0.005
HF-CT2_21_1	0.011	1527.300	0.009	-0.008
HF-CT2_21_2	0.011	1532.300	0.008	-0.008
HF-CT2_21_3	0.011	1537.298	0.007	-0.007
HF-CT2_21_4	0.011	1542.284	0.008	-0.006
HF-CT2_21_5	0.011	1547.293	0.008	-0.007
HF-CT2_21_6	0.012	1552.264	0.008	-0.006
HF-CT2_21_7	0.012	1557.258	0.006	-0.005
HF-CT2_21_8	0.012	1562.274	0.005	-0.004
HF-CT2_21_9	0.012	1567.246	0.005	-0.005
HF-CT2_22_1	0.011	1527.297	0.010	-0.011
HF-CT2_22_2	0.011	1532.300	0.009	-0.009
HF-CT2_22_3	0.011	1537.297	0.009	-0.010
HF-CT2_22_4	0.012	1542.284	0.008	-0.011
HF-CT2_22_5	0.012	1547.293	0.009	-0.009
HF-CT2_22_6	0.012	1552.262	0.008	-0.008
HF-CT2_22_7	0.012	1557.257	0.008	-0.007
HF-CT2_22_8	0.012	1562.274	0.006	-0.008
HF-CT2_22_9	0.012	1567.246	0.006	-0.007

Table 2: HF-CT2 Sensors Calibration Data

While checking the calibration data for the Sensor 31_1, and after filtering the obtained measurements, we found that there is something similar to a hysteresis effect (Figure 21). These effects impacted the accuracy of our results leading to a high deviation of the measured data from the fitting curve. As observed in Figure 20 for a certain temperature, the wavelength obtained are spread over a large range, with a maximum deviation of +31.76 pm and -27.6 pm (Table 1) which highly impacts the precision of the measurements obtained by these sensors. As seen in Figure 22, the wavelength obtained from the sensor at the first cycle is significantly higher than the one obtained at the second cycle for the same temperature. It is also worth mentioning that the same problem occurs for sensors 32_1 and 41_1 but does not happen for 42_1 and the remaining sensors.

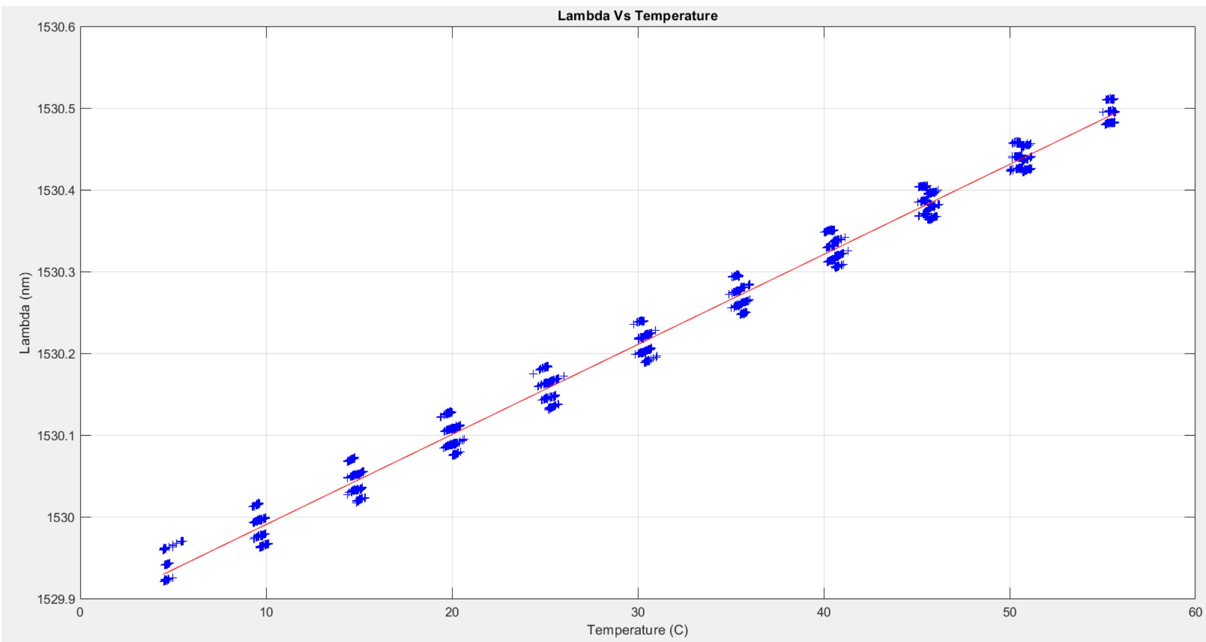


Figure 20: Endcap 31_1 Sensor Lambda vs Temperature

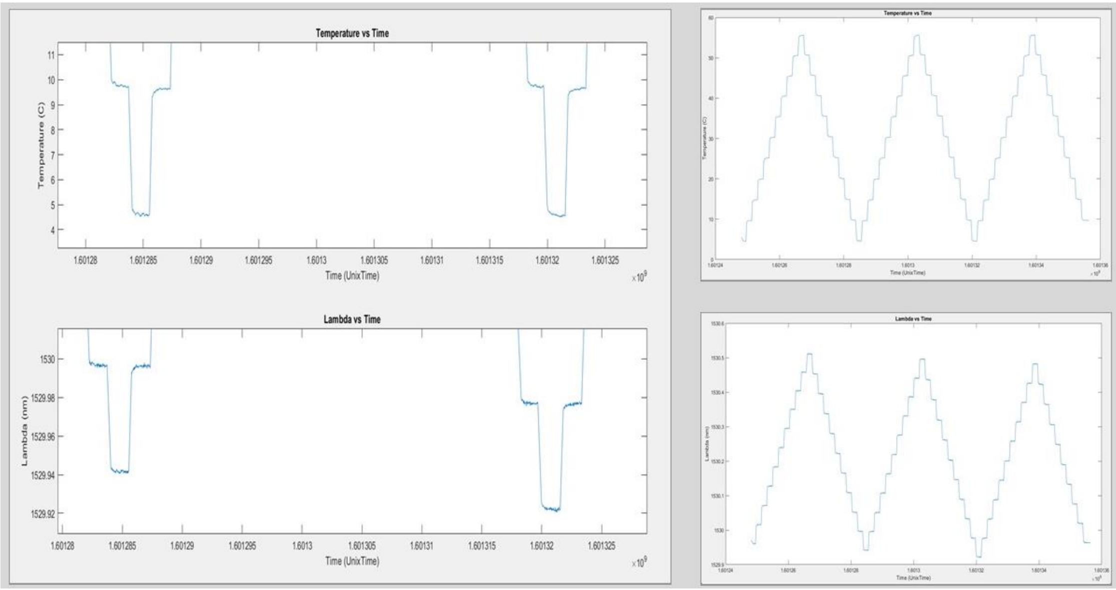


Figure 21: Endcap 31_1 Deviation of Measured data from the Fitting Curve

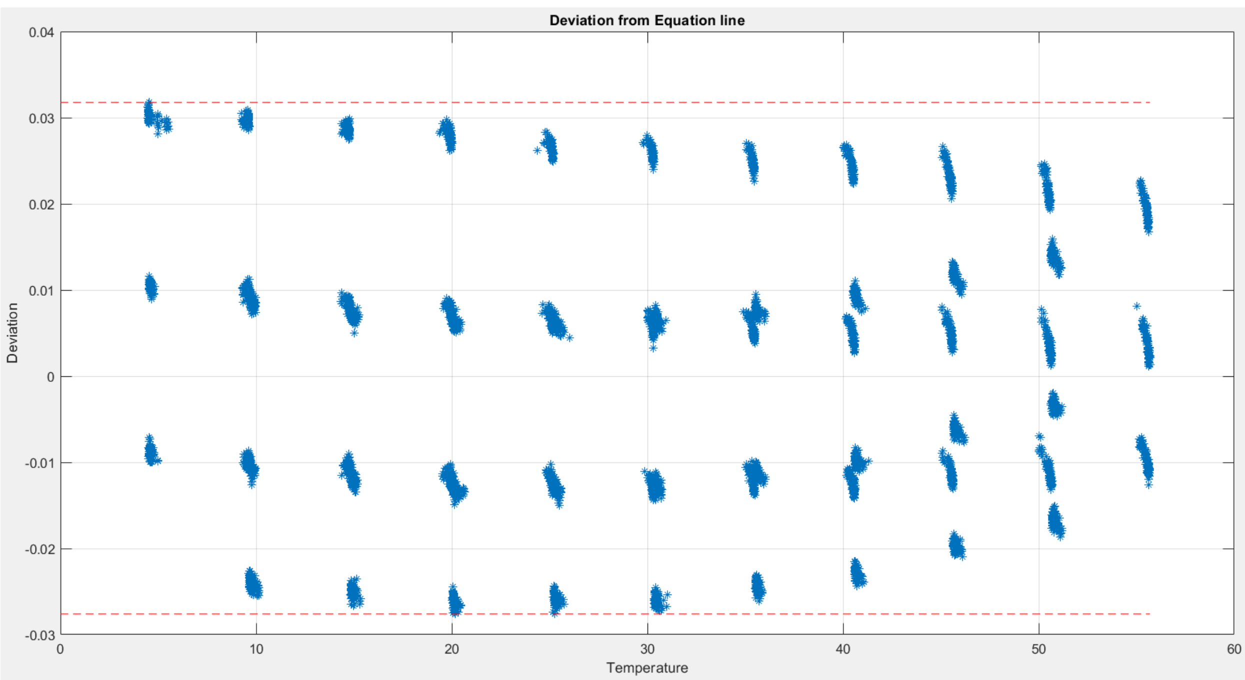


Figure 22: Endcap 31_1 Temperature and Wavelength vs Time

Furthermore, we checked the data for only 1 full cycle and ½ a cycle for the EndCap_31 array to see if the problem also occurs with the first sensor (EndCap_31_1). As observed in Table 3, the maximum and minimum deviation for sensor 31_1 decreased significantly, but the sensor is still behaving in a different manner than other sensors of the same array. However, for the data of only ½ a cycle(Table 4), we can see that deviation of 31_1 also decreases from the value it was for

1 full cycle, and it is also clear that this sensor is behaving almost similar to the others on the same array.

FBG	P1	P2	Max Deviation (nm)	Min Deviation (nm)
EndCap_31_1	0.011	1529.899	0.013	-0.013
EndCap_31_2	0.011	1534.911	0.005	-0.007
EndCap_31_3	0.011	1539.871	0.005	-0.007
EndCap_31_4	0.011	1544.850	0.005	-0.007
EndCap_31_5	0.011	1549.885	0.006	-0.006
EndCap_31_6	0.011	1554.855	0.005	-0.006
EndCap_31_7	0.011	1559.855	0.003	-0.002
EndCap_31_8	0.011	1564.761	0.003	-0.003

Table 3: EndCap_31 One Cycle Calibration Data

FBG	P1	P2	Max Deviation (nm)	Min Deviation (nm)
EndCap_31_1	0.011	1529.912	0.004	-0.003
EndCap_31_2	0.011	1534.914	0.002	-0.002
EndCap_31_3	0.011	1539.875	0.003	-0.002
EndCap_31_4	0.011	1544.853	0.003	-0.003
EndCap_31_5	0.011	1549.888	0.003	-0.002
EndCap_31_6	0.011	1554.858	0.003	-0.003
EndCap_31_7	0.011	1559.855	0.003	-0.002
EndCap_31_8	0.011	1564.761	0.003	-0.003

Table 4: EndCap_31 Half Cycle Calibration Data

With the sensors used on the HF-CT2 we did not face the previously mentioned problem. However, for both HF-CT2_11 and 12 arrays, we obtained a Deviation slightly higher than the ones obtained in other arrays which is not so problematic, and we can deal with it. (Table 2).

To conclude, all data received was acceptable since the deviation from the calibration curve was small. Except for the 3 problematic FBGs Endcap_31_1, Endcap_32_1, and Endcap_41_1. However, this problem is not a serious issue, since the calibration constants are reasonable and almost similar to the other sensors. In addition, this problem does not appear in any of the other sensors, it might be due to the way they were placed in the climatic chamber, or to some dust restricting the movement of the sensor in the capillary tube, thus causing some strain, and affecting the readings. To solve this issue, it is suggested to take the calibration constants of the 1 cycle data points show in Table 5. The validation for the three problematic sensors should be done in the next month by taking data from them to see if the readings are reasonable.

FBG	P1	P2
EndCap_31_1	0.011	1529.899
EndCap_32_1	0.011	1530.035
EndCap_41_1	0.011	1527.350

Table 5: New Calibration Constants for Problematic Sensors

6 Recalibration

For the Central Beam pipe, it was not possible to put its sensors in the climatic chamber in order to get the calibration data. That is why, data was taken when the fibers are installed on the beampipe. Wavelengths were acquired for short period of time for all the sensors before (Figure 23) and after stretching them(Figure 24). Note that only the ends of the horizontal array are tightened. Hence, as shown in(Figure 25) even after tightening the arrays, central regions remain hanging not too far from the beampipe, but most probably not on it.

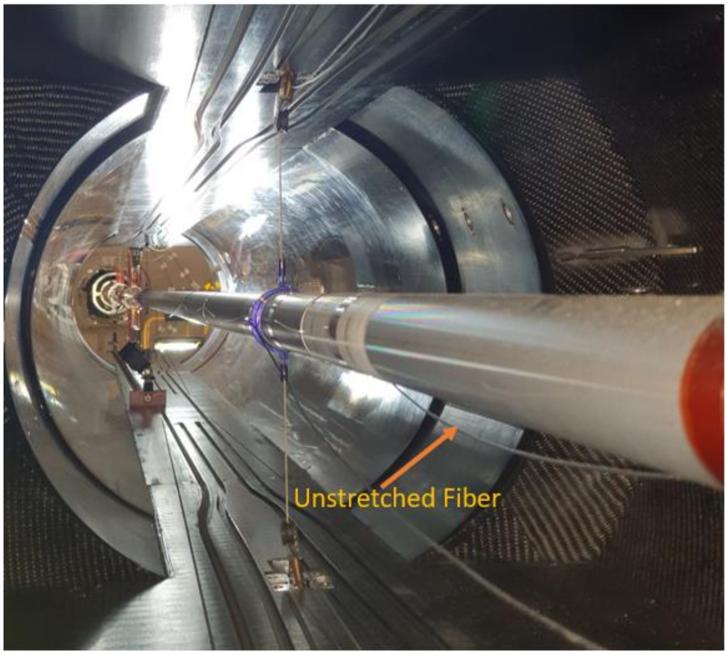


Figure 23: Central Beampipe before stretching the fiber.

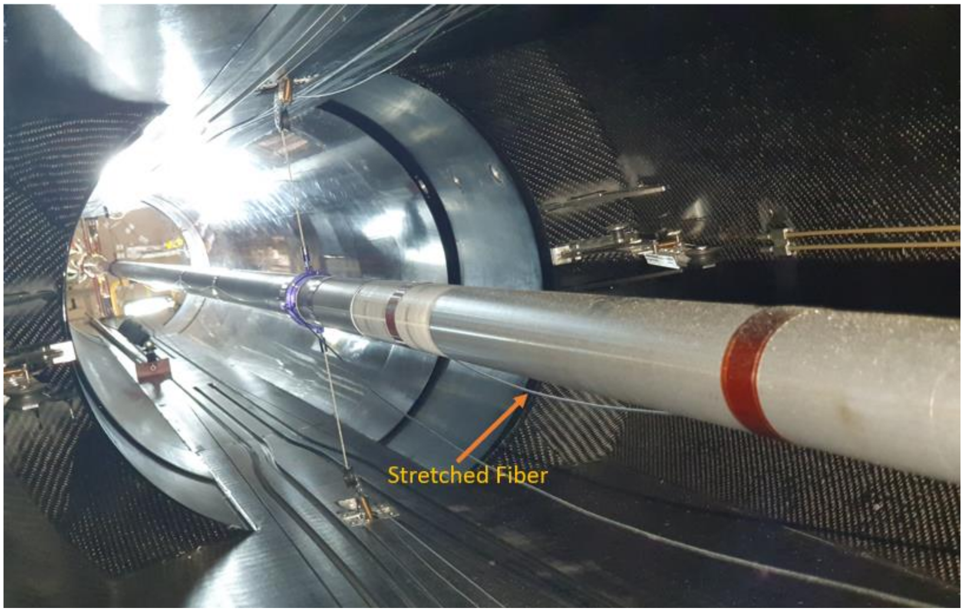


Figure 24: Central Beampipe after stretching the fiber.

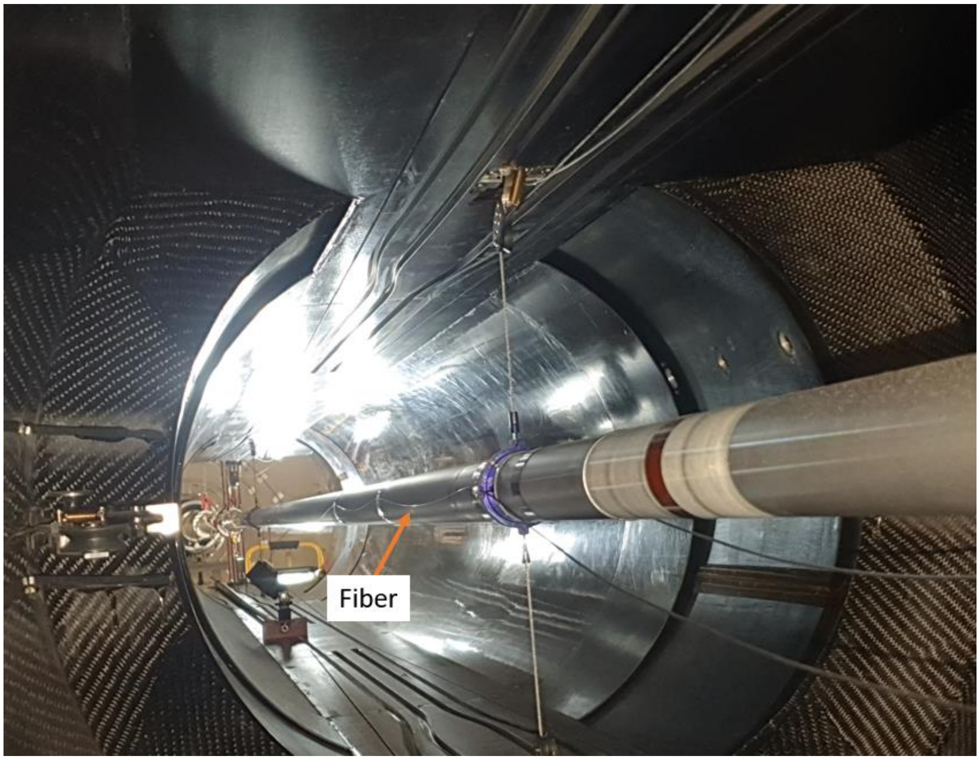


Figure 25: Central Region of the Fiber after stretching.

Using the PT1000 installed on a fishing rod (Figure 26), the T0 values were acquired, each at a certain distance on the beam pipe and at a certain time. To calculate our calibration equation, we first assumed the wavelength change with respect to temperature to be 0.01 nm/˚C (P1). Next, we also assumed that the temperature was constant along the pipe at a certain moment. Then the first T0 readings both before and after stretching the fiber were taken (T0=16.81˚C and 18.06˚C respectively). Then, the wavelength recorded at approximately the same time of the acquisition of T0 was used as the respective wavelength of this T0 value.

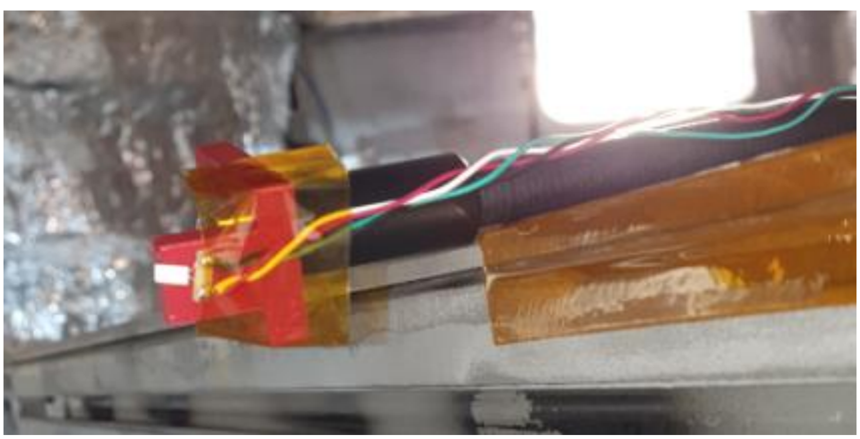


Figure 26: PT1000 on a Fishing Rod

Using this equation $\lambda(nm) = P1 * T(°C) + P2$, and with λ, P1, and T already defined at T0, P2 was calculated, and the values obtained are shown in Table 6. As we can see, P2 experienced a remarkable change for the sensors on both ends of the Central BP, and almost a negligible change for the sensors in the middle. This validates our result because only the sensors on the ends are stretched inducing a strain effect and affecting their P2. Figure 27 and Figure 28 show the change in Wavelength and Temperature with respect to time, in addition to the change in wavelength with respect to temperature both before and after stretching the fiber, respectively.

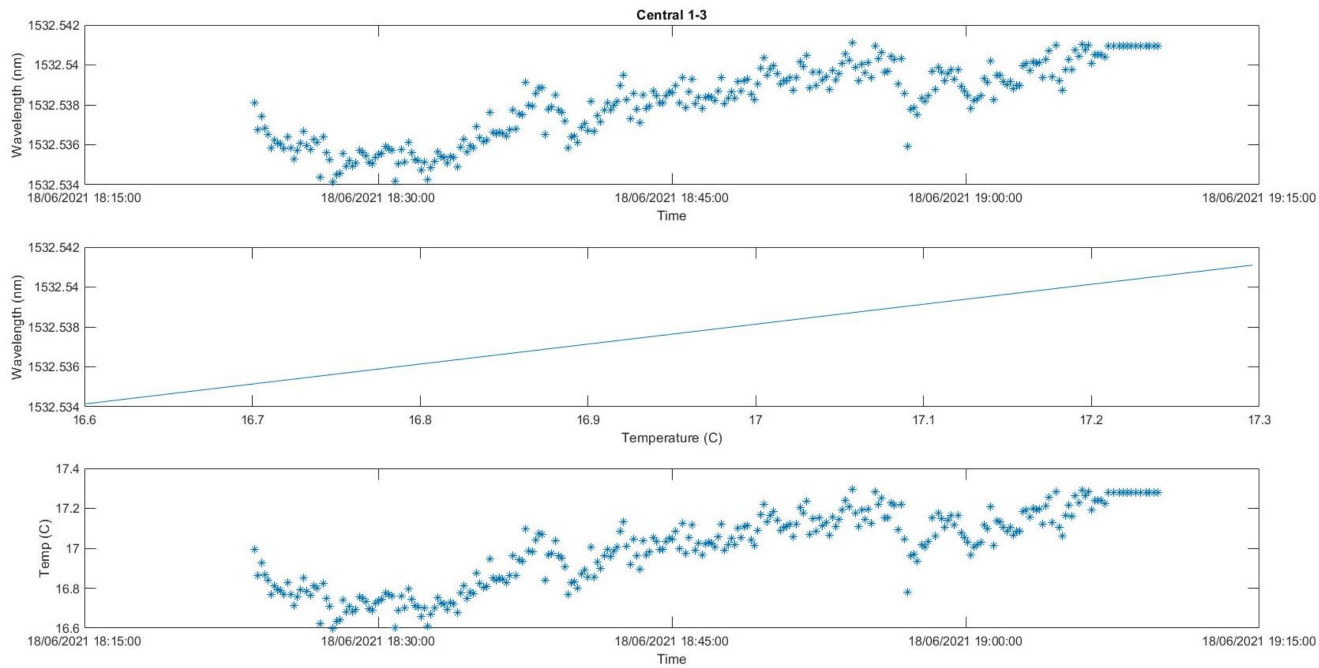


Figure 27: Central_1_3 before stretching.

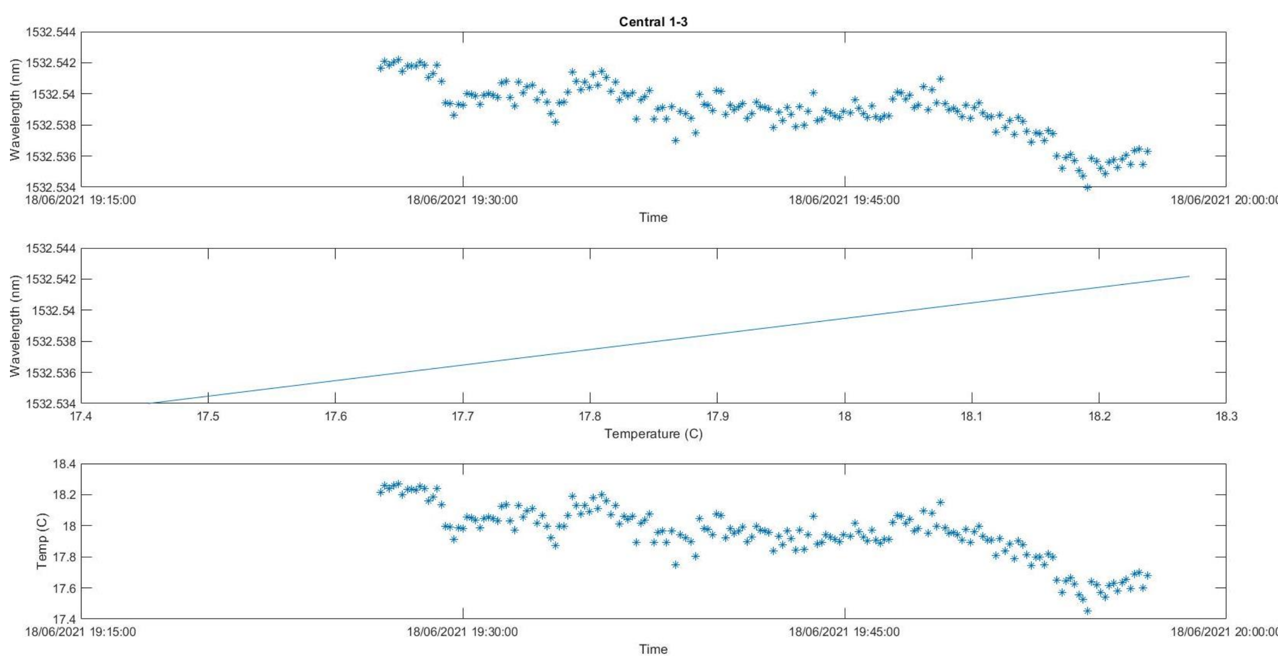


Figure 28: Central_1_3 After Stretching

FBG	P1	P2 (Before Stretching)	P2 (After Stretching)	Change in P2
Central_1_1	0.010	1522.329	1522.931	0.602
Central_1_2	0.010	1527.347	1527.741	0.394
Central_1_3	0.010	1532.368	1532.359	-0.009
Central_1_4	0.010	1537.310	1537.302	-0.009
Central_1_5	0.010	1542.240	1542.233	-0.008
Central_1_6	0.010	1547.205	1547.194	-0.012
Central_1_7	0.010	1552.237	1552.227	-0.010
Central_1_8	0.010	1557.337	1557.328	-0.008
Central_1_9	0.010	1562.324	1562.319	-0.006
Central_1_10	0.010	1567.241	1567.566	0.325
Central_1_11	0.010	1572.201	1572.462	0.261
Central_2_1	0.010	1524.813	1524.802	-0.011
Central_2_2	0.010	1529.789	1529.778	-0.011
Central_2_3	0.010	1535.098	1535.079	-0.019
Central_2_4	0.010	1539.798	1539.783	-0.014
Central_2_5	0.010	1544.887	1544.876	-0.011
Central_2_6	0.010	1549.878	1549.868	-0.011
Central_2_7	0.010	1554.889	1554.880	-0.009
Central_2_8	0.010	1560.067	1560.060	-0.006
Central_2_9	0.010	1565.088	1565.082	-0.006
Central_2_10	0.010	1569.678	1569.670	-0.009
Central_2_11	0.010	1574.644	1574.636	-0.008

Table 6: Central Beampipe Calibration Constants

7 Bakeout Data Acquisition

For the HF-CT2 we were able to make recalibration measurements before the bakeout. From the plots shown in 9.39.3 we can see that considering the recalibration measurements, all sensors give us a temperature close to 17˚C which is the real temperature. However, if we use the calibration parameters obtained without the recalibration, the sensors are giving us nonphysical number, varying between 5˚C and 22˚C while they all are at the same temperature. This proves the recalibration done before the bakeout solve many mechanical problems caused by the installation. Table 7 presents a summary of the data received with recalibration or without recalibration of the sensors.

		With Recalibration		Without Recalibration	
FBG	P1	P2 (λ0) (nm)	Temperature before bakeout (˚C)	P2 (λ0) (nm)	Temperature before bakeout (˚C)
HF-CT2_12_1	0.011	1529.815	22.5	1529.881	16.6
HF-CT2_12_2	0.011	1534.804	20.2	1534.842	16.7
HF-CT2_12_3	0.011	1539.810	16.5	1539.805	17.0
HF-CT2_12_4	0.011	1544.786	13.0	1544.740	17.0
HF-CT2_12_5	0.011	1549.772	10.4	1549.696	17.0
HF-CT2_12_6	0.011	1554.772	5.1	1554.637	16.8
HF-CT2_12_7	0.012	1559.738	7.3	1559.632	16.6
HF-CT2_12_8	0.012	1564.744	12.7	1564.700	16.5
HF-CT2_12_9	0.012	1569.740	19.7	1569.780	16.3
HF-CT2_22_1	0.011	1527.297	27.0	1527.417	16.5
HF-CT2_22_2	0.011	1532.300	24.4	1532.388	16.8
HF-CT2_22_3	0.011	1537.297	17.6	1537.305	17.0
HF-CT2_22_4	0.012	1542.284	17.5	1542.289	17.0
HF-CT2_22_5	0.012	1547.293	11.8	1547.232	17.1
HF-CT2_22_6	0.012	1552.262	9.2	1552.172	16.9
HF-CT2_22_7	0.012	1557.257	7.7	1557.153	16.5
HF-CT2_22_8	0.012	1562.274	11.4	1562.216	16.4
HF-CT2_22_9	0.012	1567.246	17.9	1567.266	16.2

Table 7: HF-CT2 #2 Bakeout data Summary

Similar to the HF-CT2, the Endcap FBGs also suffered faced the same issue of having different temperatures at the beginning and the end of the Bakeout varying between 3 and 14 ˚C as shown in Table 8. However, since for both endcaps we do not have the temperature data before the bakeout to compensate for the changes occurring due to the installation, we decided to use the temperature data we measured after the bakeout 9.3.2. By recalibrating the Endcap sensors, we are compensating for the mechanical constraints caused by the bakeout itself which led to some negative temperature readings in many sensors which is illogical and impossible to happen and achieving close temperatures for all the sensors on the Endcap at a certain period of time (around 14.5 to 15˚C) .

		Without Recalibration		With Recalibration	
FBG	P1	P2 (λ0) (nm)	Temperature After Bakeout (˚C)	P2 (λ0) (nm)	Temperature After Bakeout (˚C)
EndCap_31_1	0.011	1529.880	3.8	1529.762	14.6
EndCap_31_2	0.011	1534.908	3.5	1534.786	14.6
EndCap_31_3	0.011	1539.868	5.1	1539.763	14.7
EndCap_31_4	0.011	1544.847	8.7	1544.780	14.7
EndCap_31_5	0.011	1549.882	9.0	1549.816	14.9
EndCap_31_6	0.011	1554.854	9.9	1554.800	14.7
EndCap_31_7	0.011	1559.850	11.9	1559.816	14.9
EndCap_31_8	0.011	1564.756	12.8	1564.729	15.2
EndCap_41_1	0.011	1527.331	3.0	1527.201	14.7
EndCap_41_2	0.011	1532.353	2.8	1532.224	14.6
EndCap_41_3	0.011	1537.319	4.9	1537.210	14.8
EndCap_41_4	0.011	1542.301	8.2	1542.227	14.9
EndCap_41_5	0.011	1547.290	8.8	1547.224	14.8
EndCap_41_6	0.011	1552.280	10.6	1552.234	14.8
EndCap_41_7	0.011	1557.269	12.1	1557.239	14.8
EndCap_41_8	0.011	1562.279	13.9	1562.264	15.2

Table 8: Endcap #1 Bakeout Data Summary

8 Conclusion

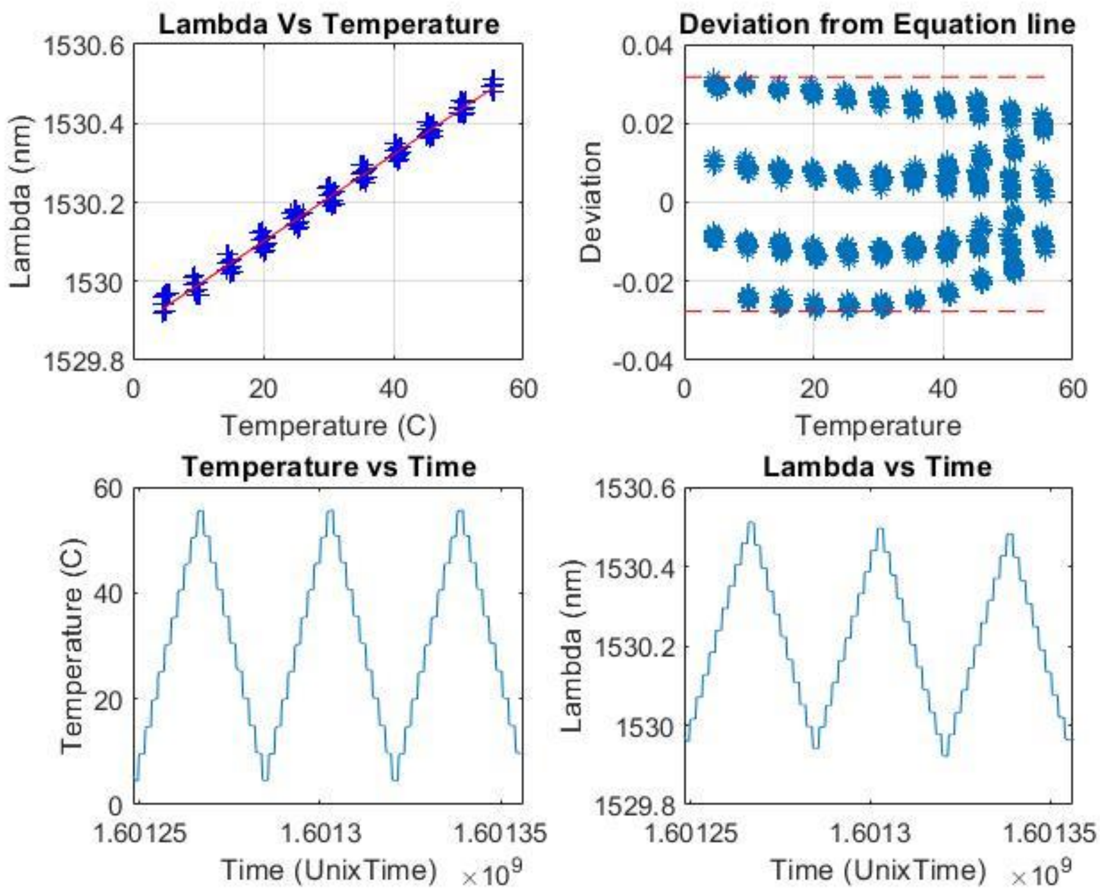
I took part in the iPipe3 project and had the task to calculate the calibration and recalibration constants of all the sensors installed on the CMS Central Beam Pipe during the LS2. In this project I performed the calibration and recalibration process of the FBG based monitoring system designed to detect temperature variations on the CMS central BP, the Endcap, and the HF-CT2. The results provide us with the calibration equation of each of the 90 FBGs of the ipipe3, proving the reliability and sensitivity of the Fiber Bragg Grating sensors used. We can conclude that the recalibration is a must after the installation in order to compensate for the mechanical impact during the installation process and after the bakeout to account for the changes occurring because of the thermal elongation caused by the high external temperatures. Finally, after the calibration and recalibration process we observe that all sensors are properly functional and ready to be used in data acquisition after the LS2. The coefficients I calculated in this project will be used in the operation of the sensors during the LHC run3.

9 Appendix

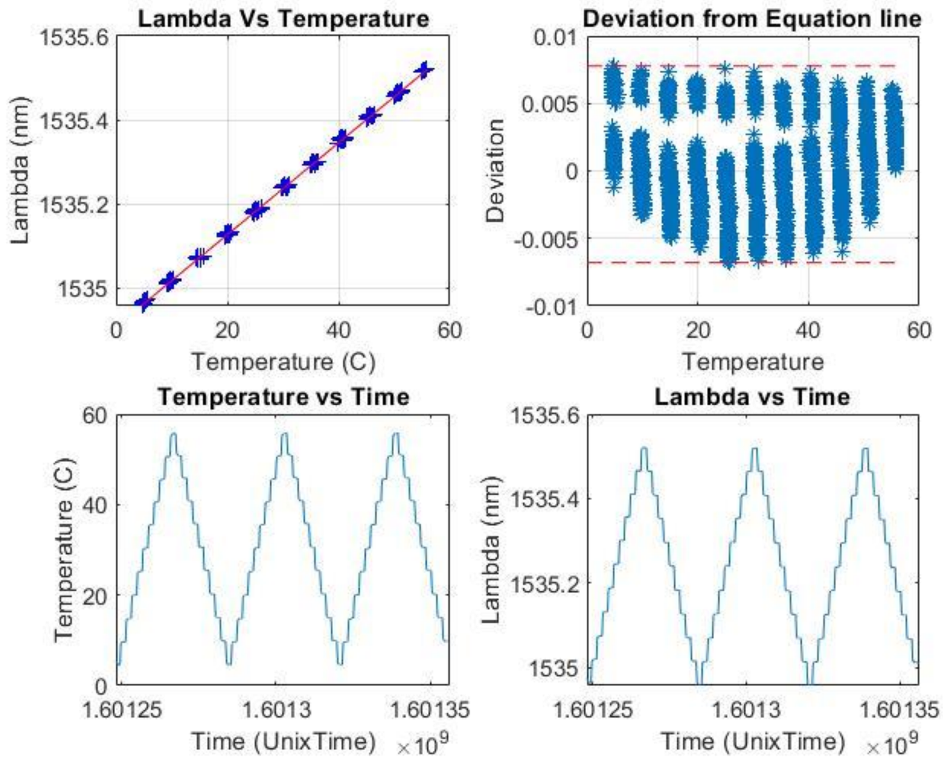
9.1 Calibration plots

9.1.1 Endcap Calibration plots

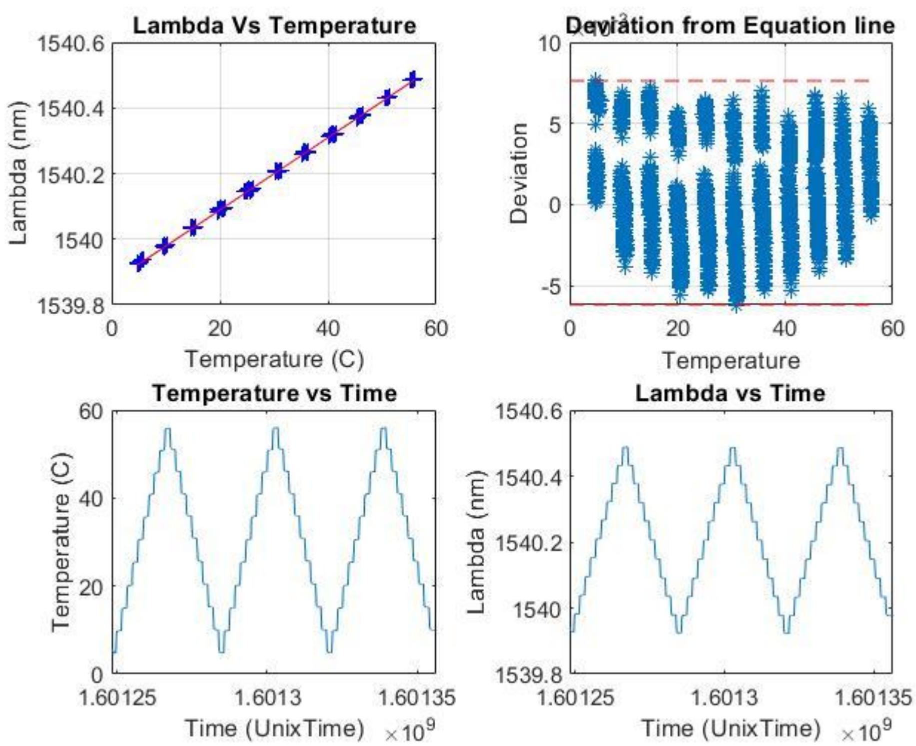
EndCap_31_1



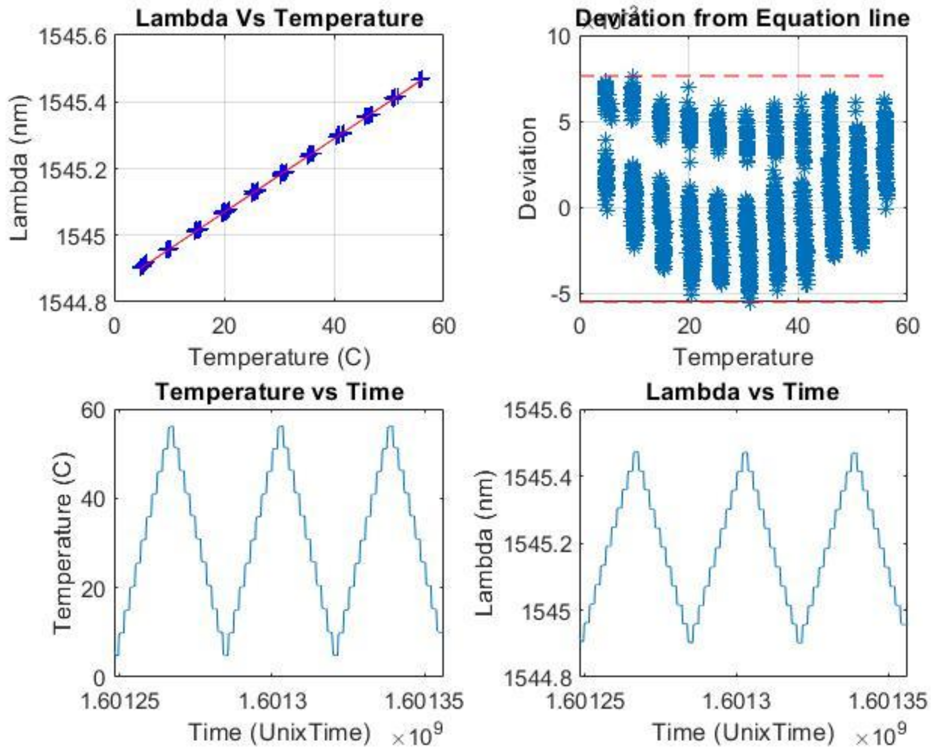
EndCap_31_2



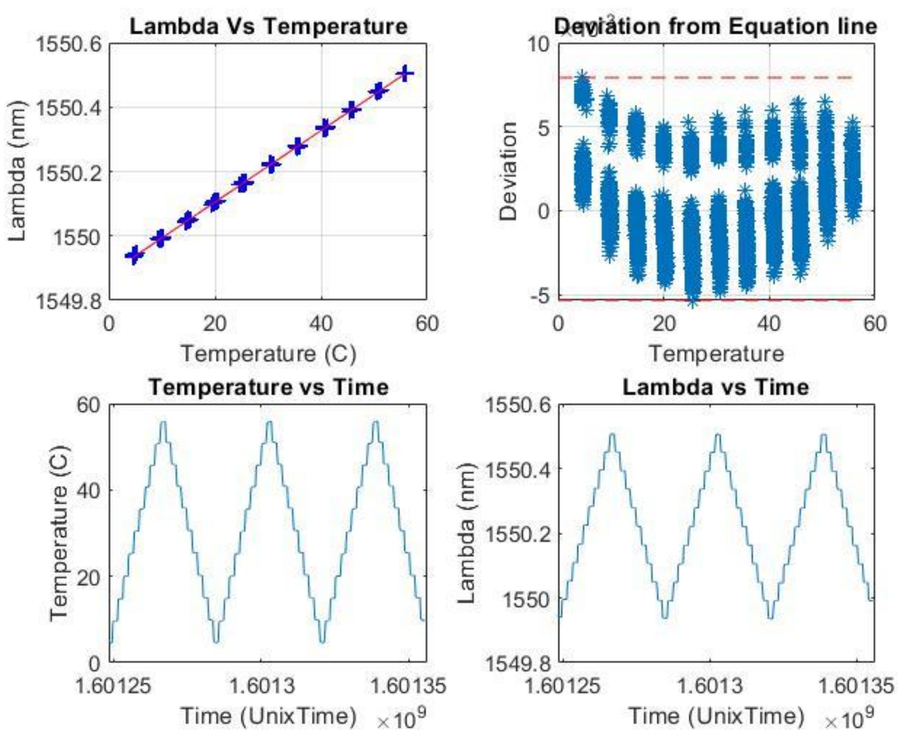
EndCap_31_3



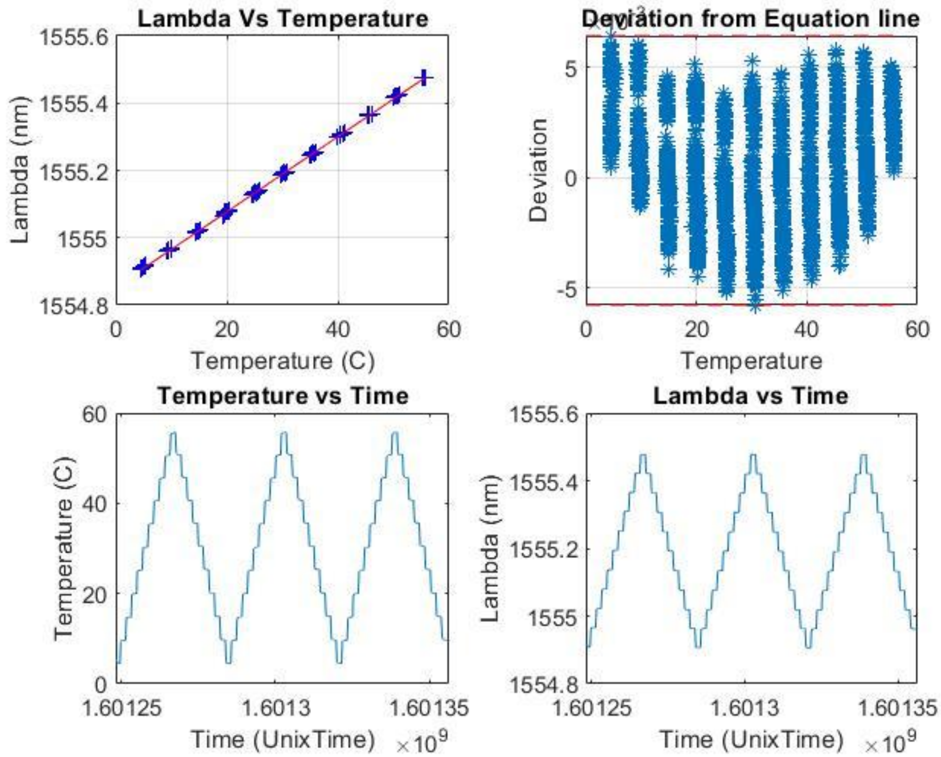
EndCap_31_4



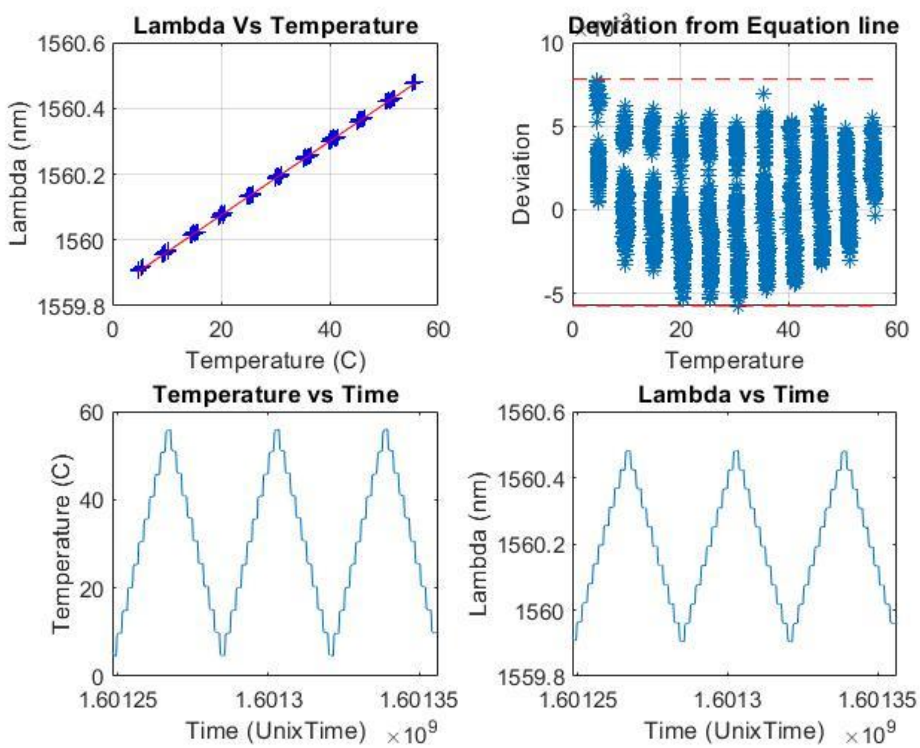
EndCap_31_5



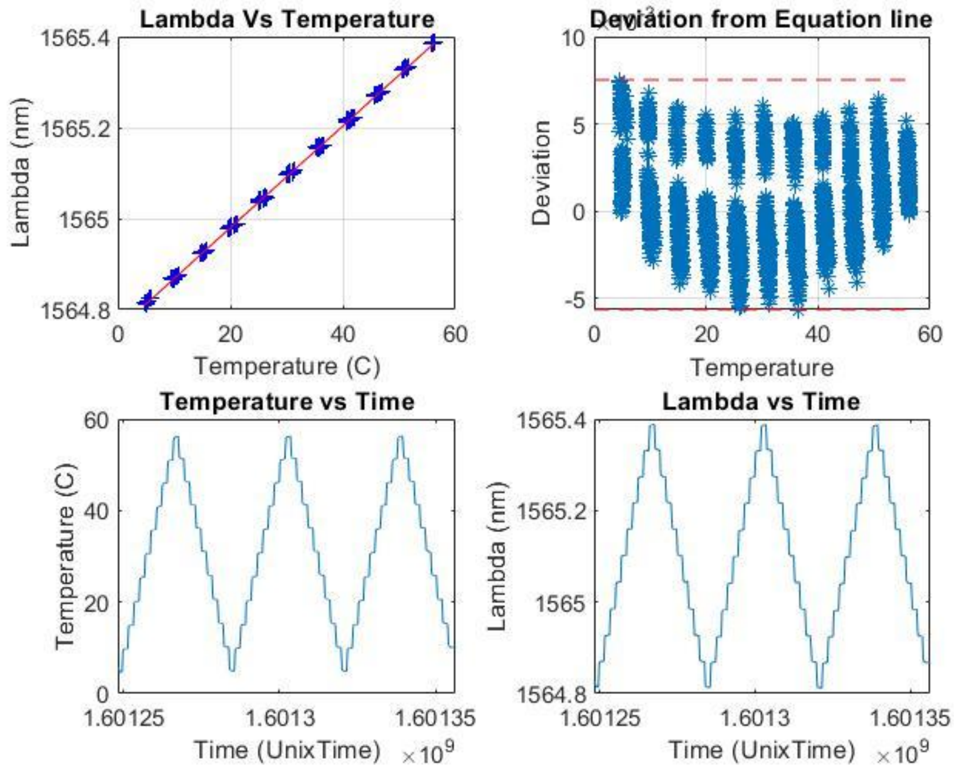
EndCap_31_6



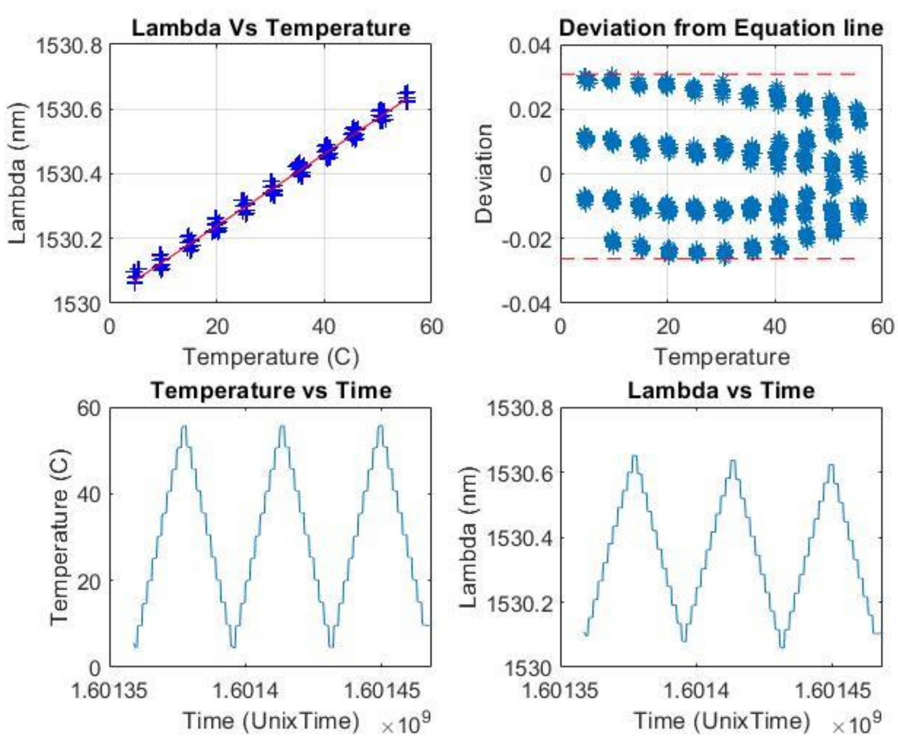
EndCap_31_7



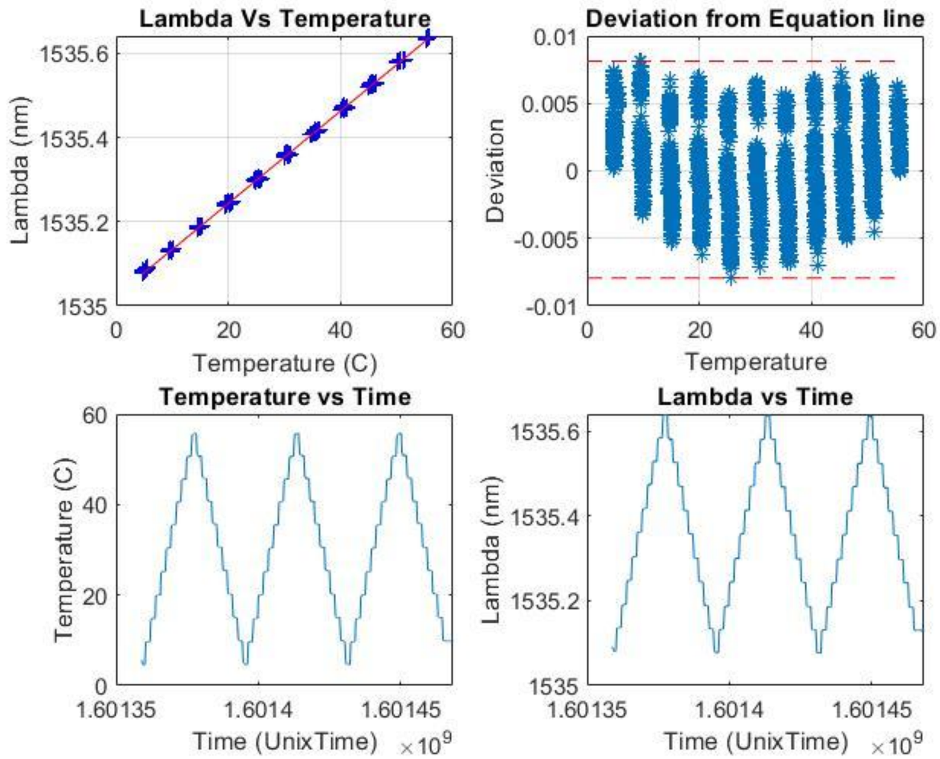
EndCap_31_8



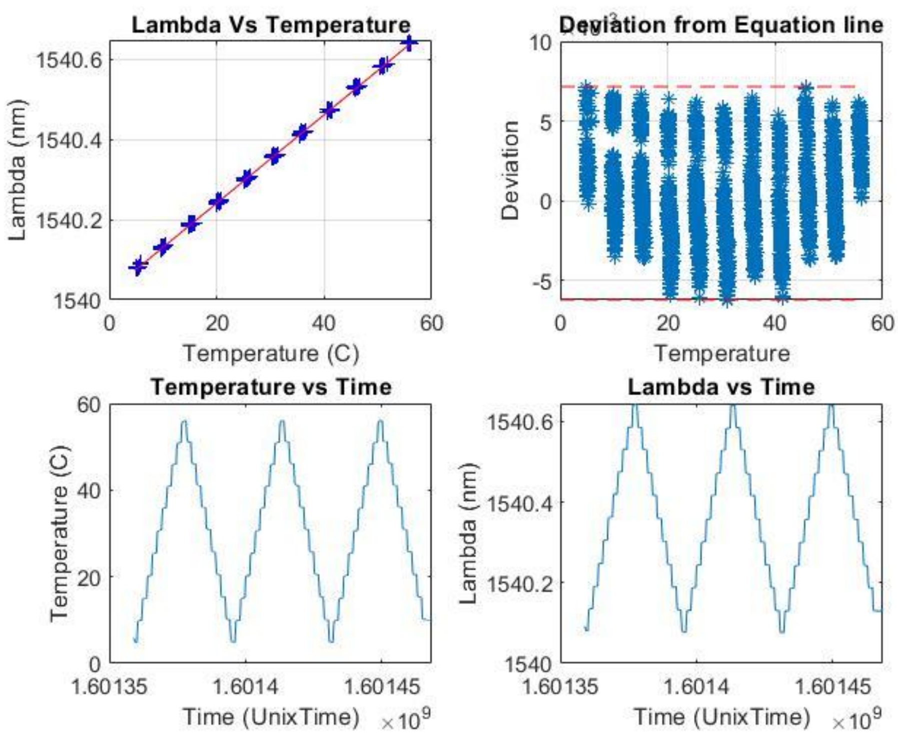
EndCap_32_1



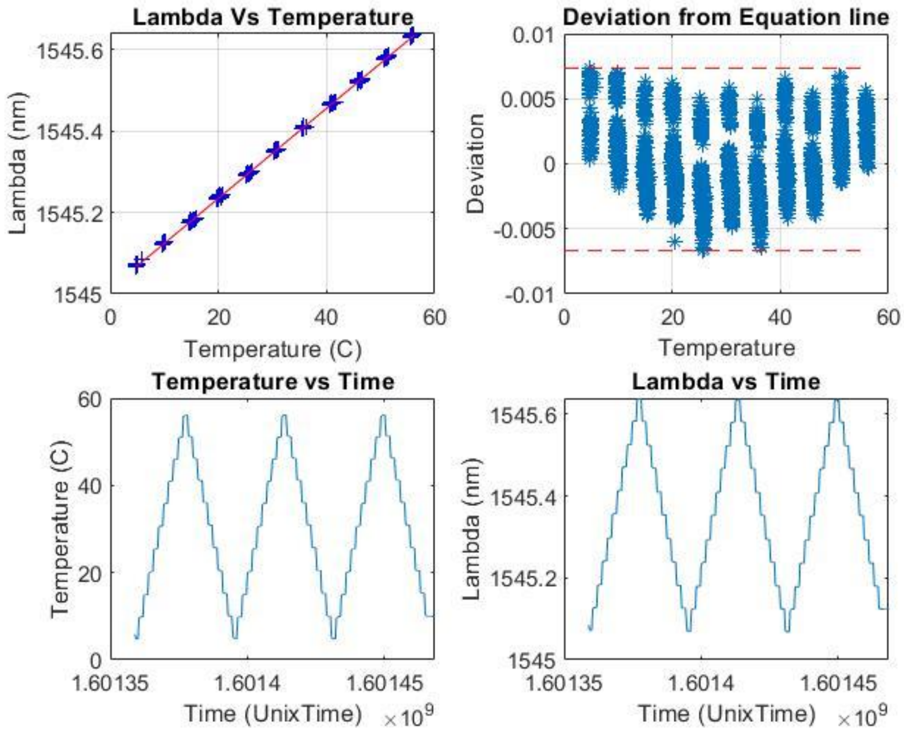
EndCap_32_2



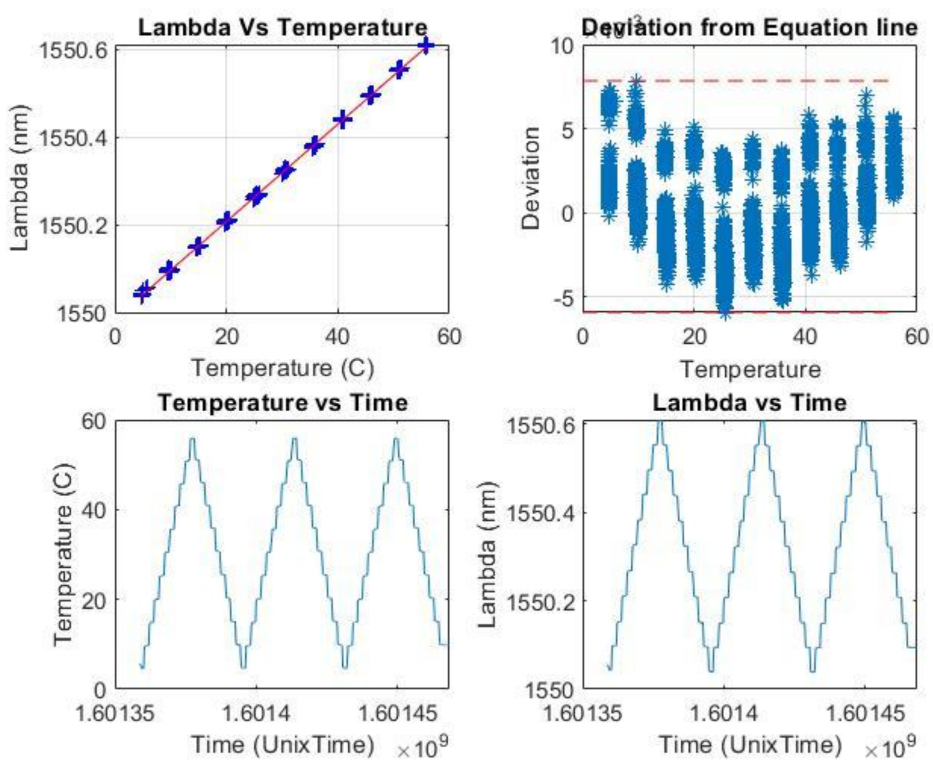
EndCap_32_3



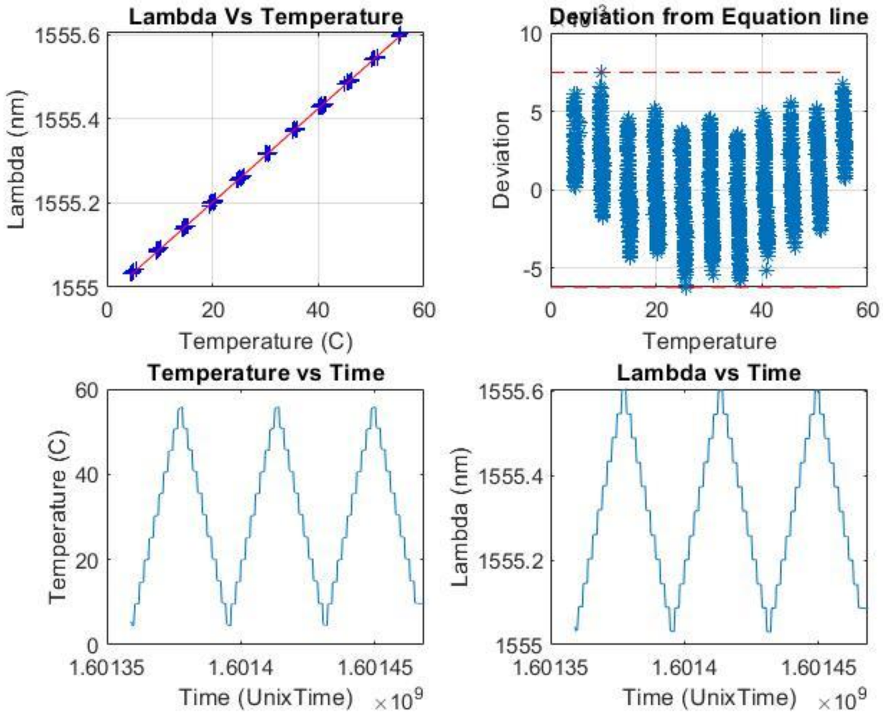
EndCap_32_4



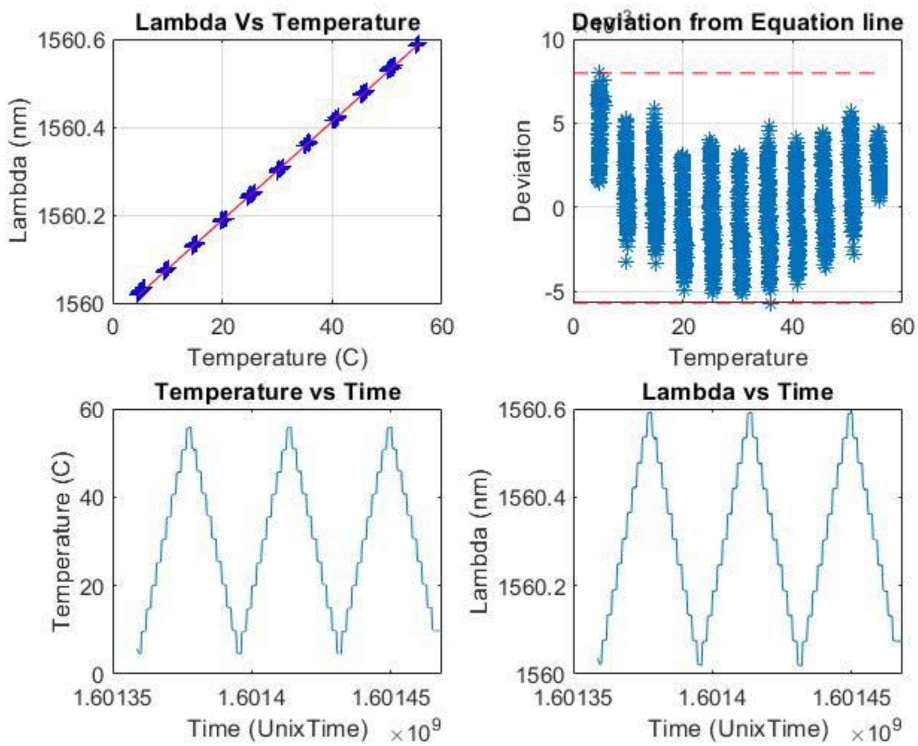
EndCap_32_5



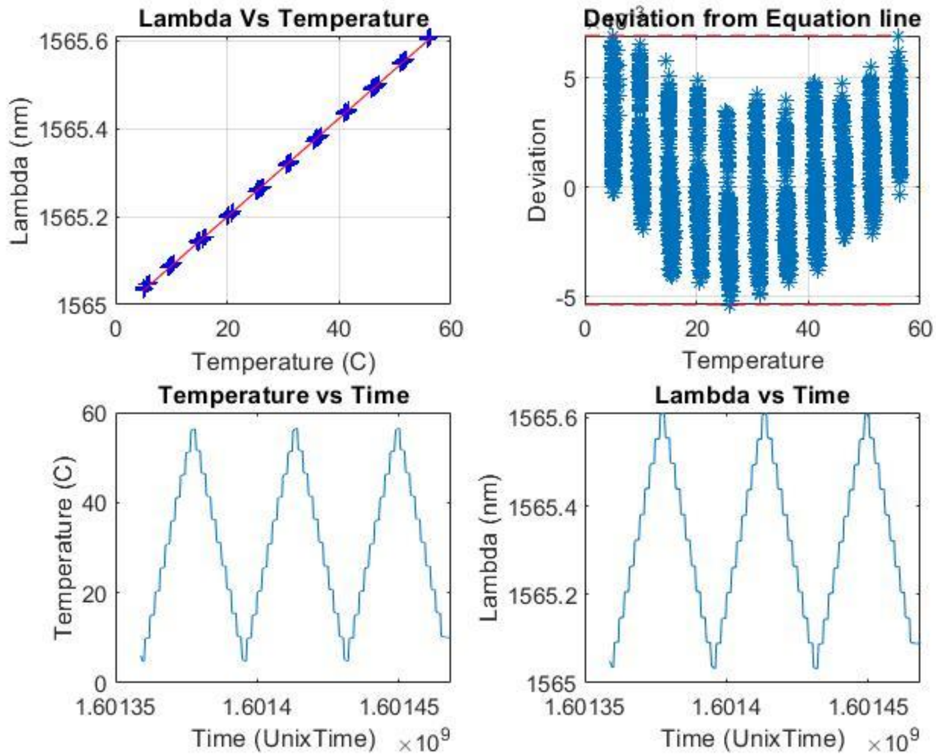
EndCap_32_6



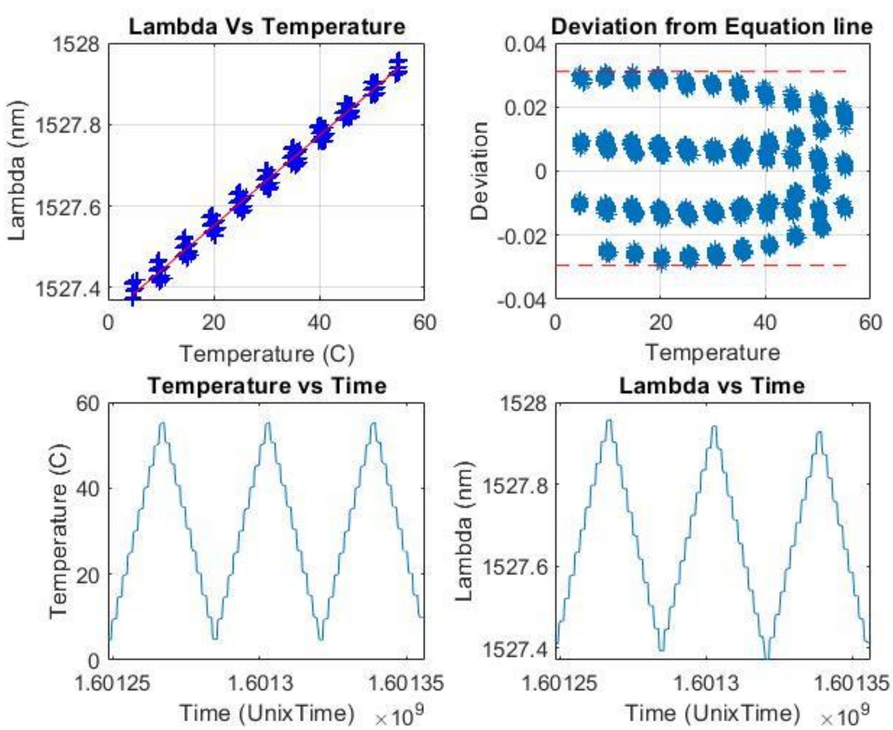
EndCap_32_7



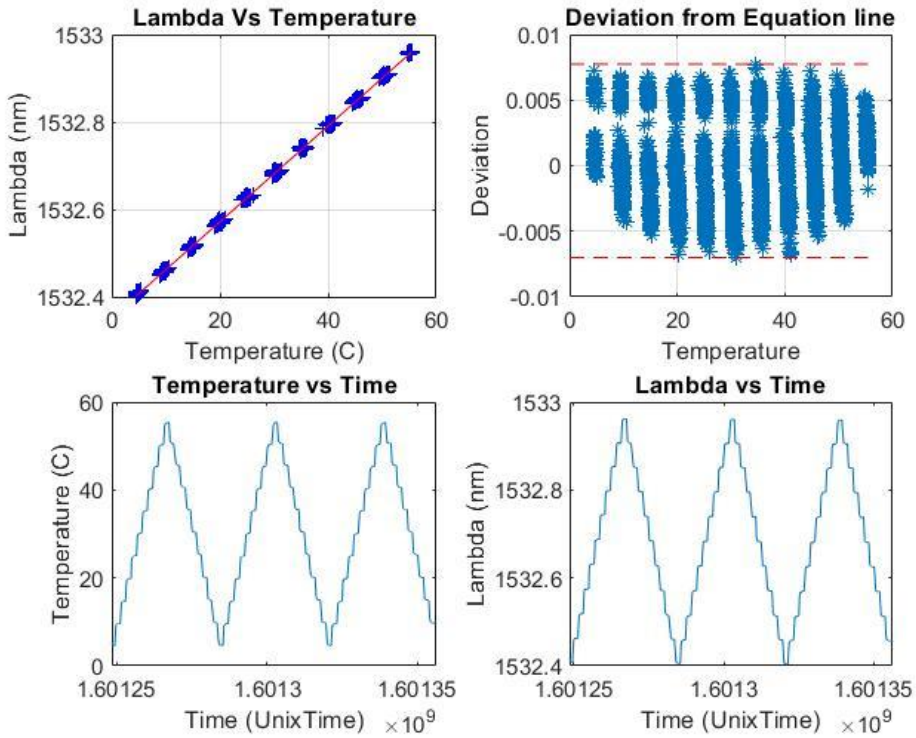
EndCap_32_8



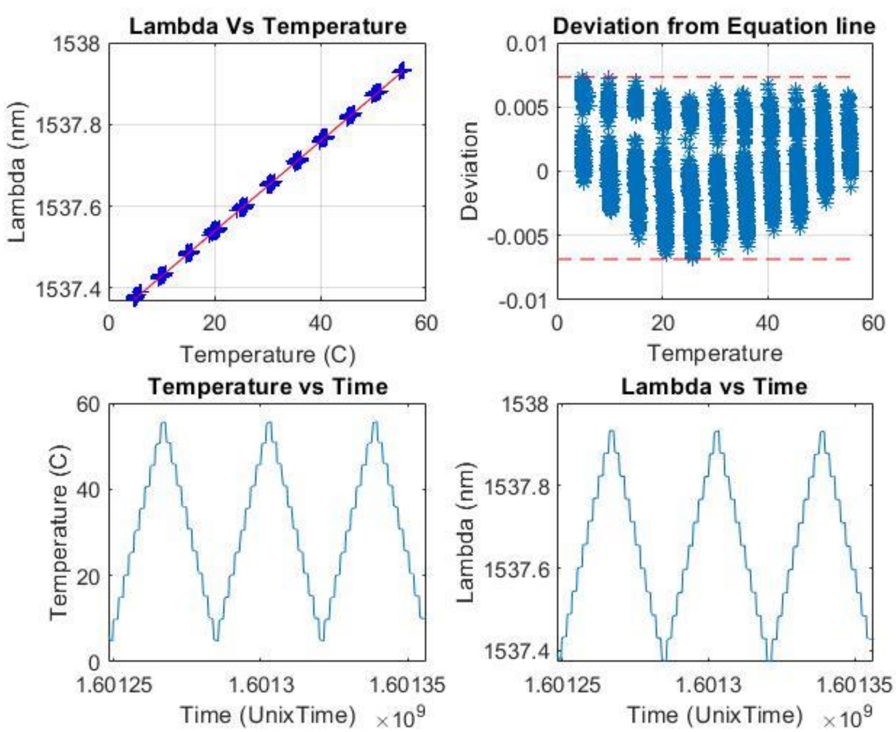
EndCap_41_1



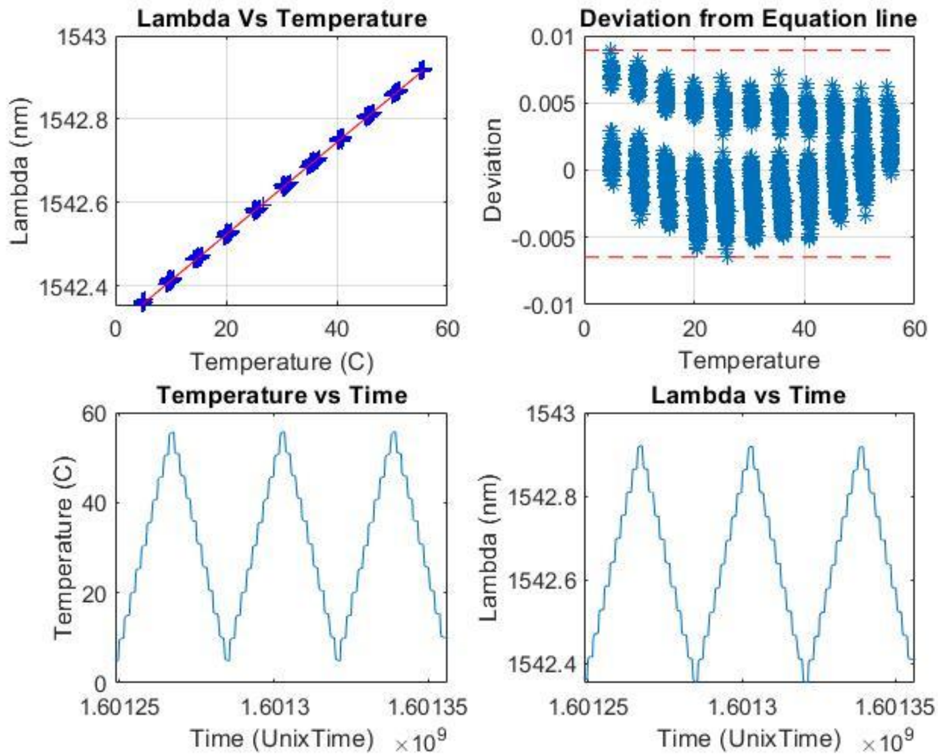
EndCap_41_2



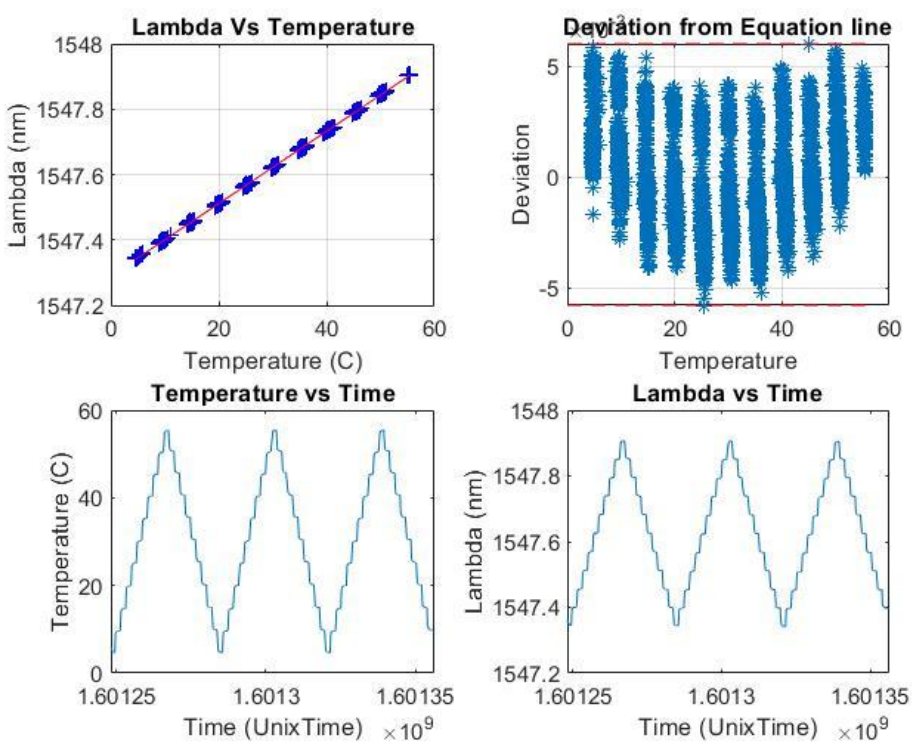
EndCap_41_3



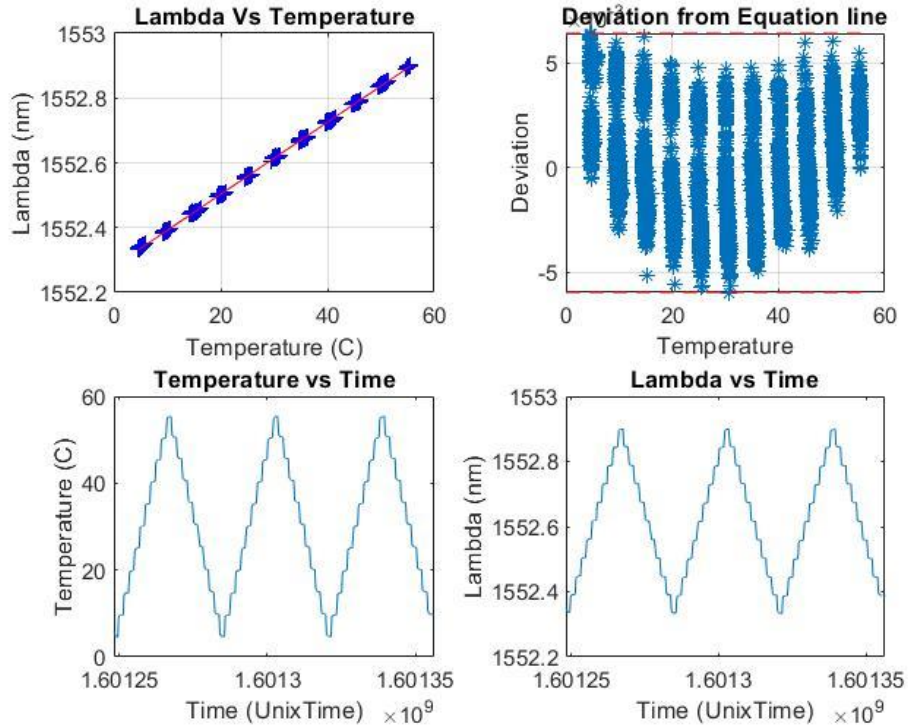
EndCap_41_4



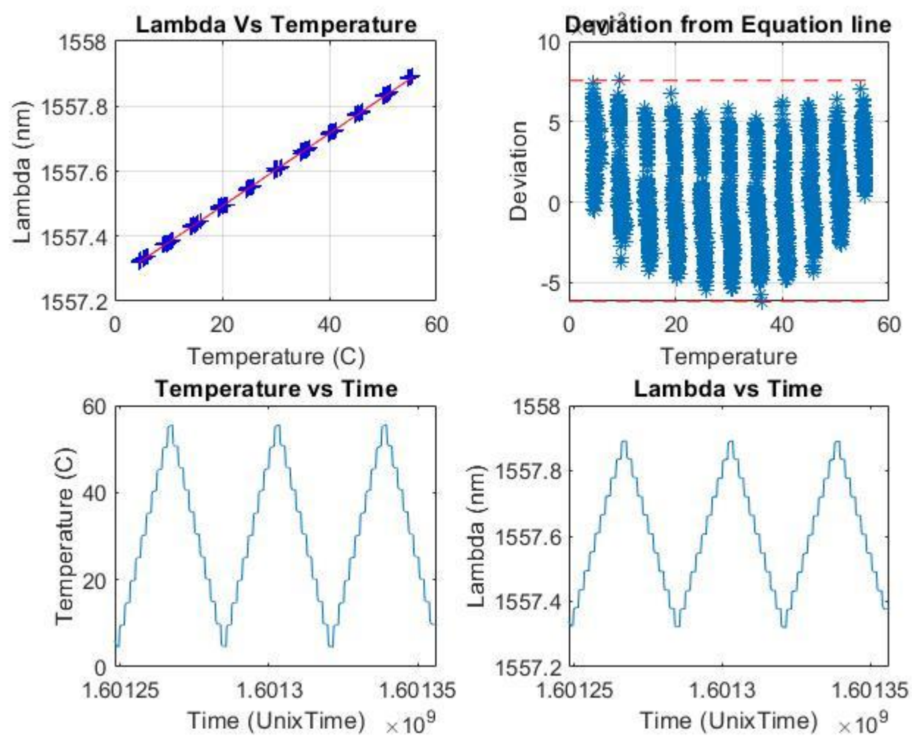
EndCap_41_5



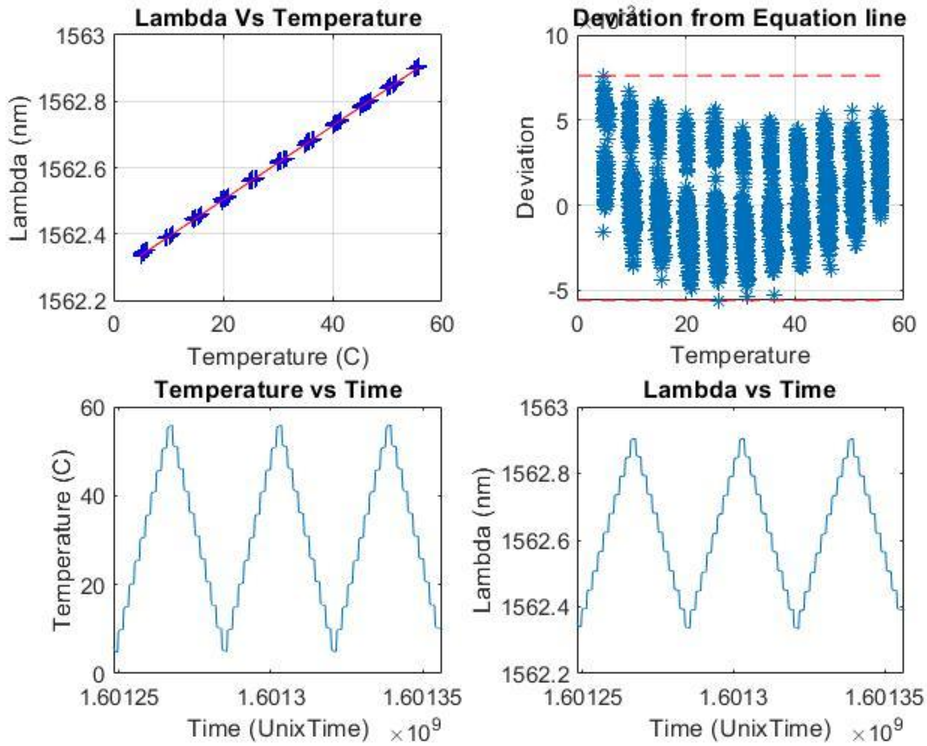
EndCap_41_6



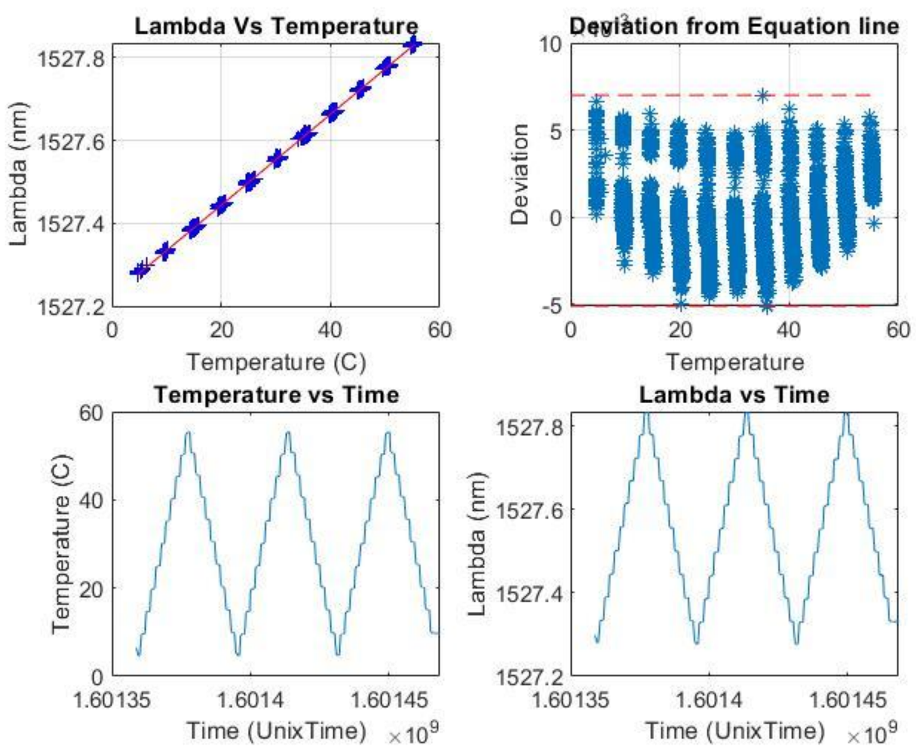
EndCap_41_7



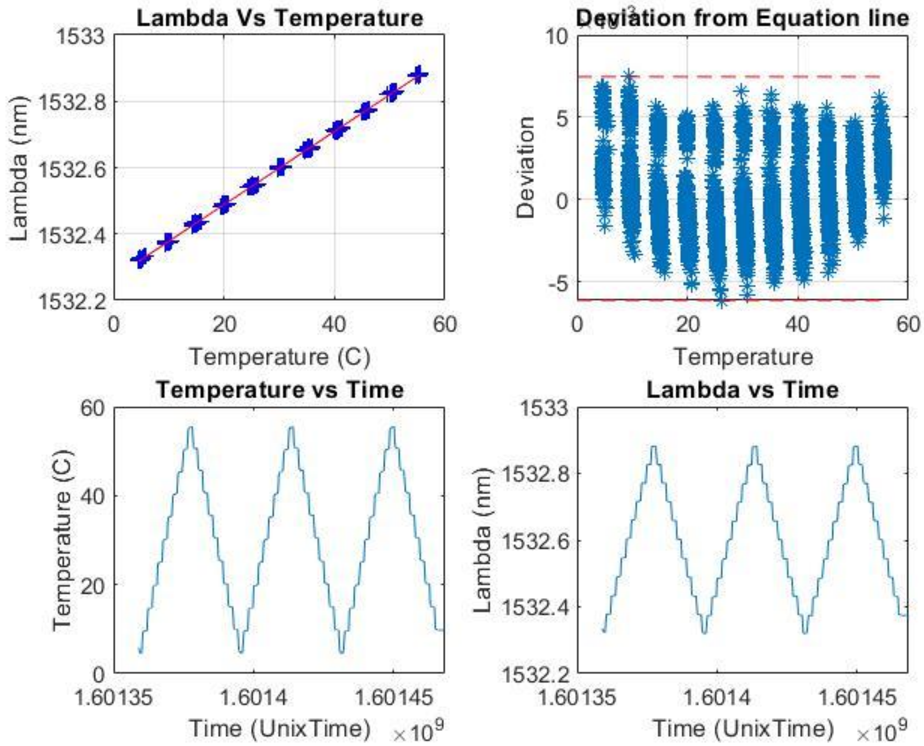
EndCap_41_8



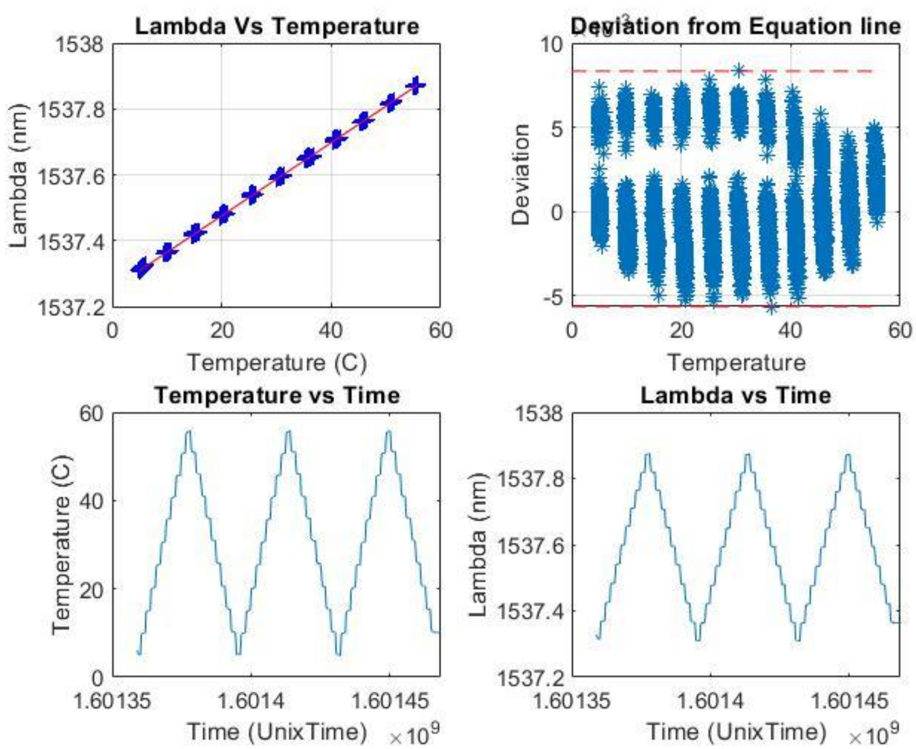
EndCap_42_1



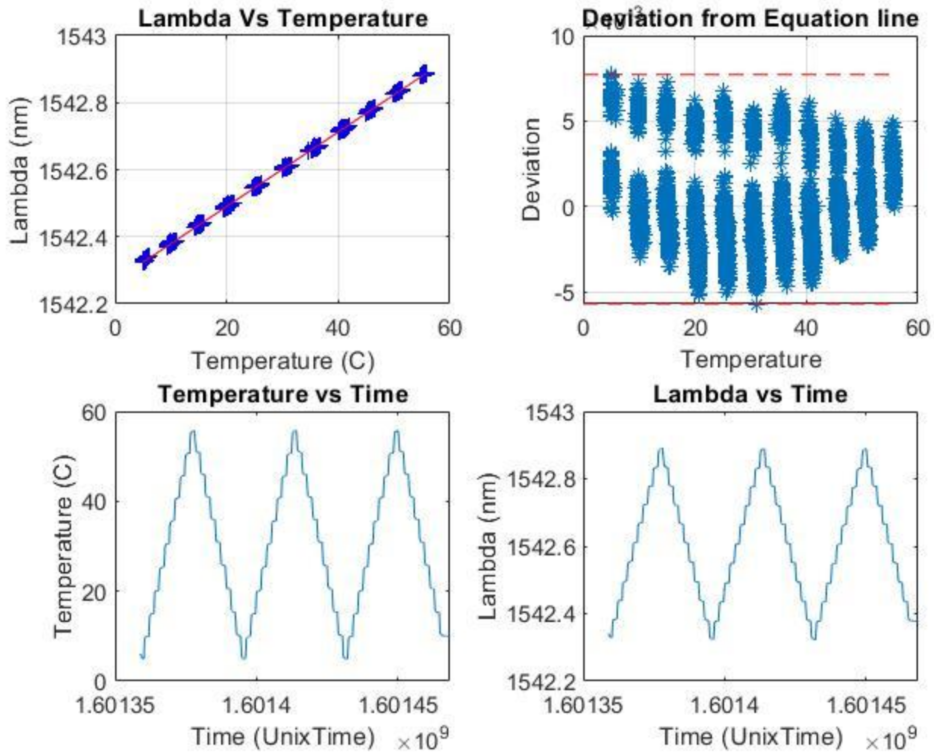
EndCap_42_2



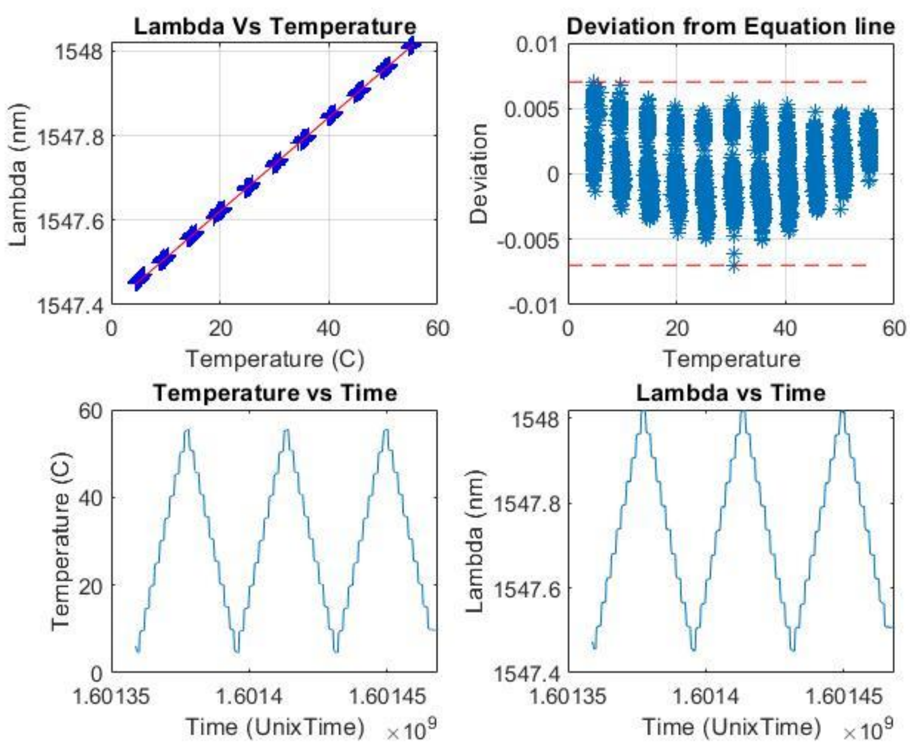
EndCap_42_3



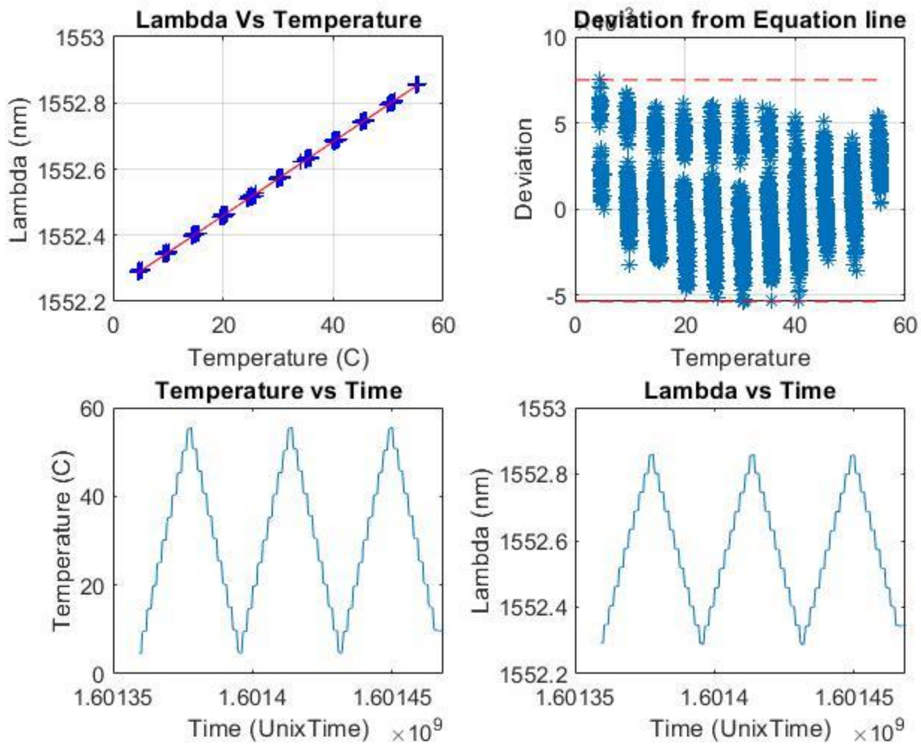
EndCap_42_4



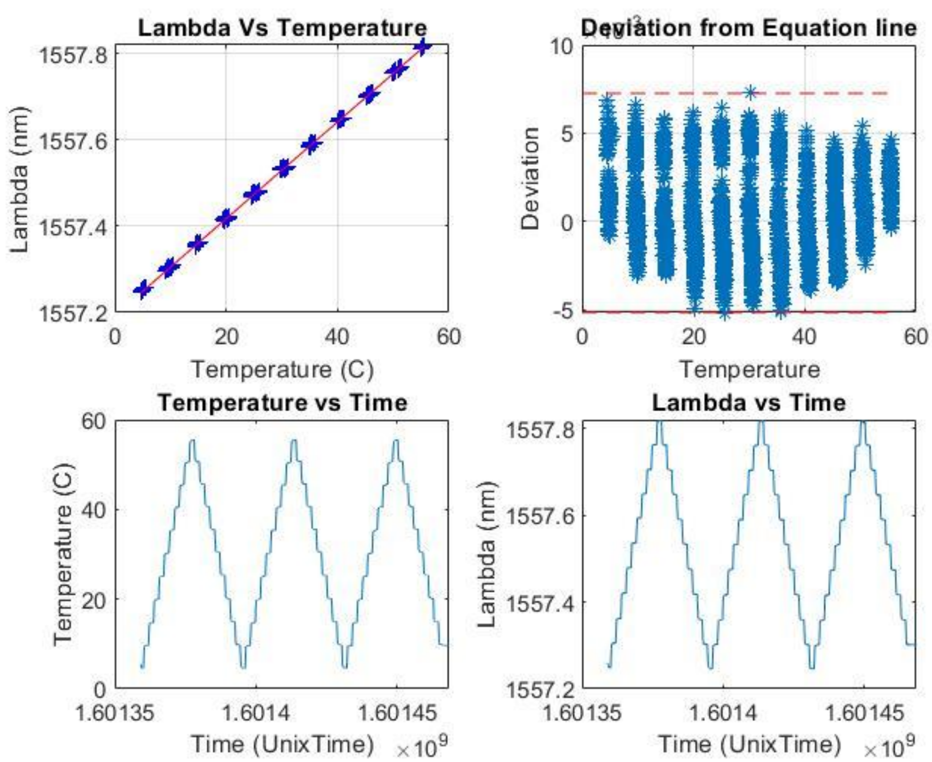
EndCap_42_5



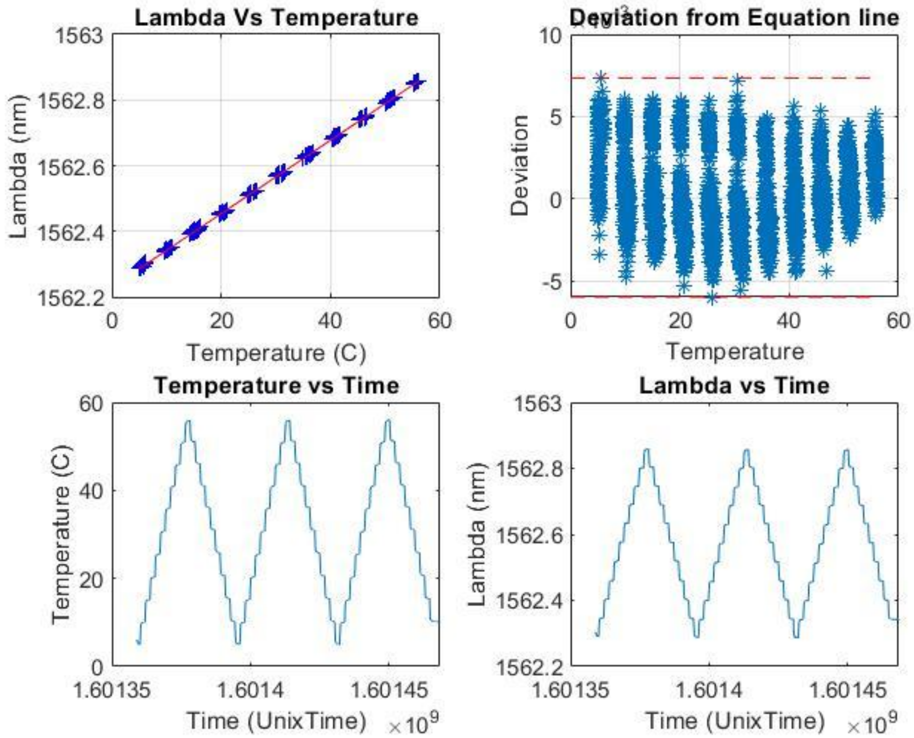
EndCap_42_6



EndCap_42_7

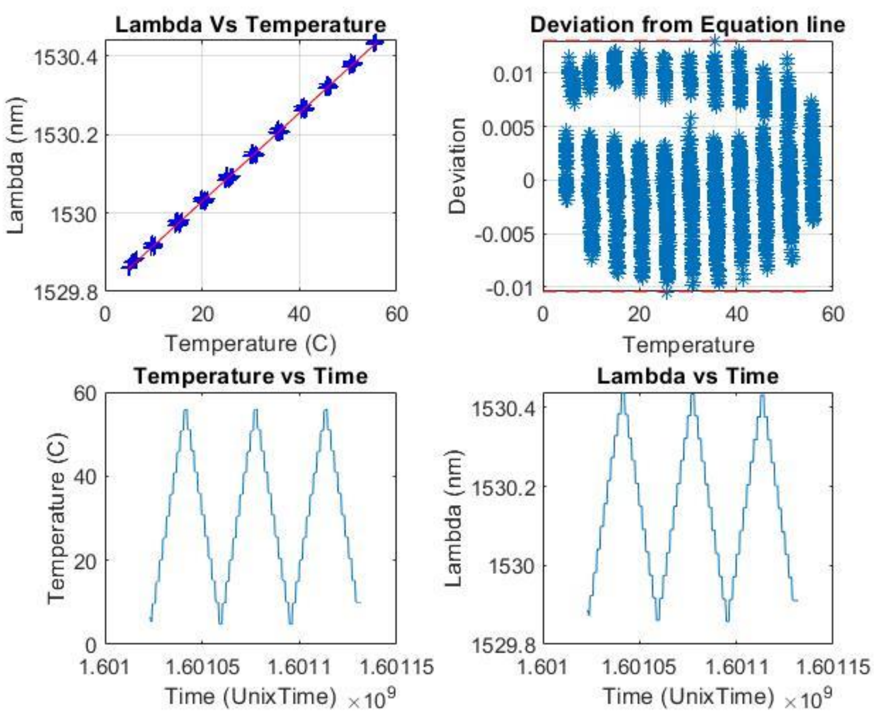


EndCap_42_8

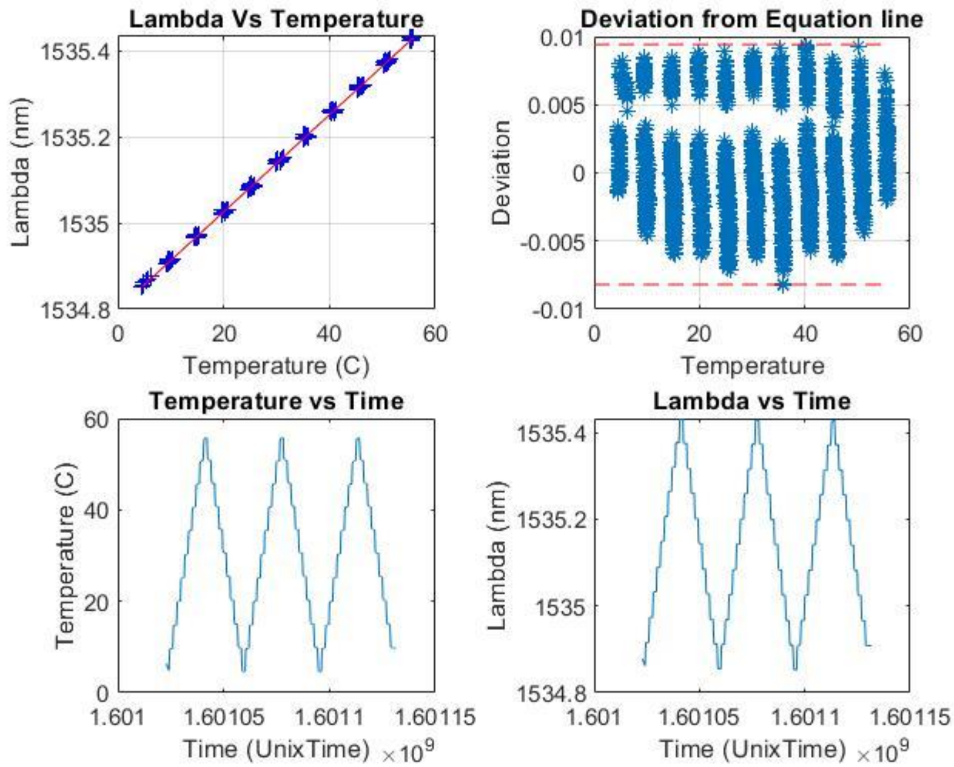


9.1.2 HF-CT2 Calibration Plots

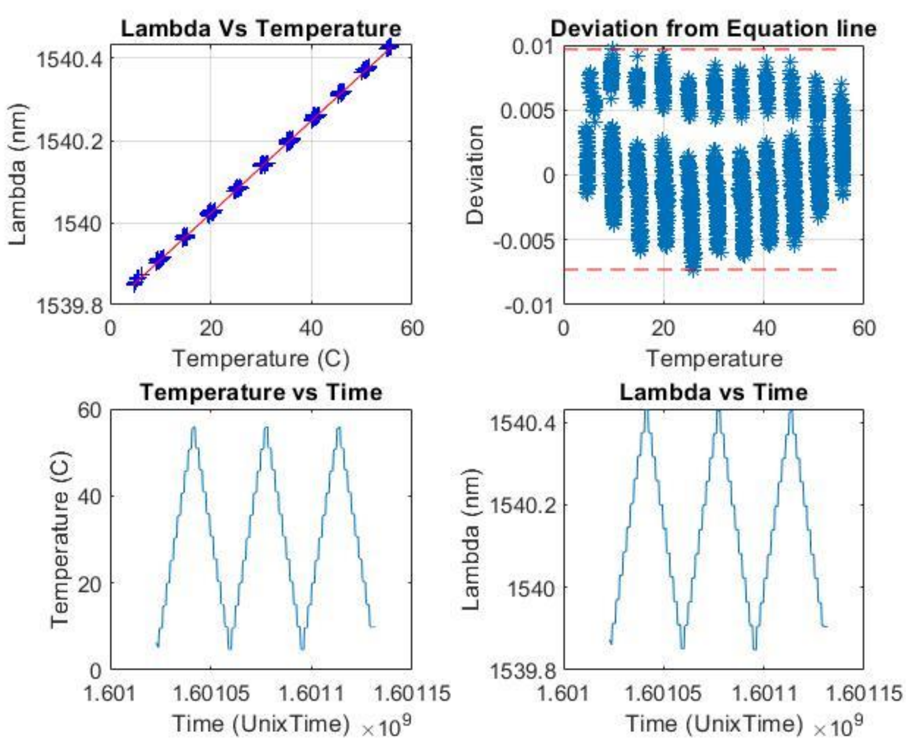
HF-CT2_11_1



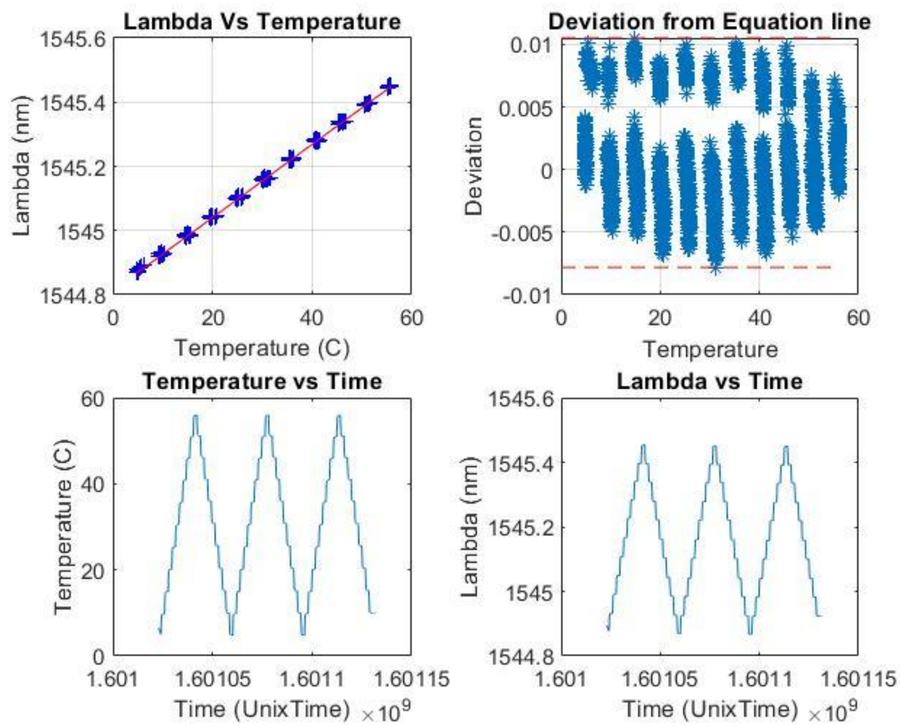
HF-CT2_11_2



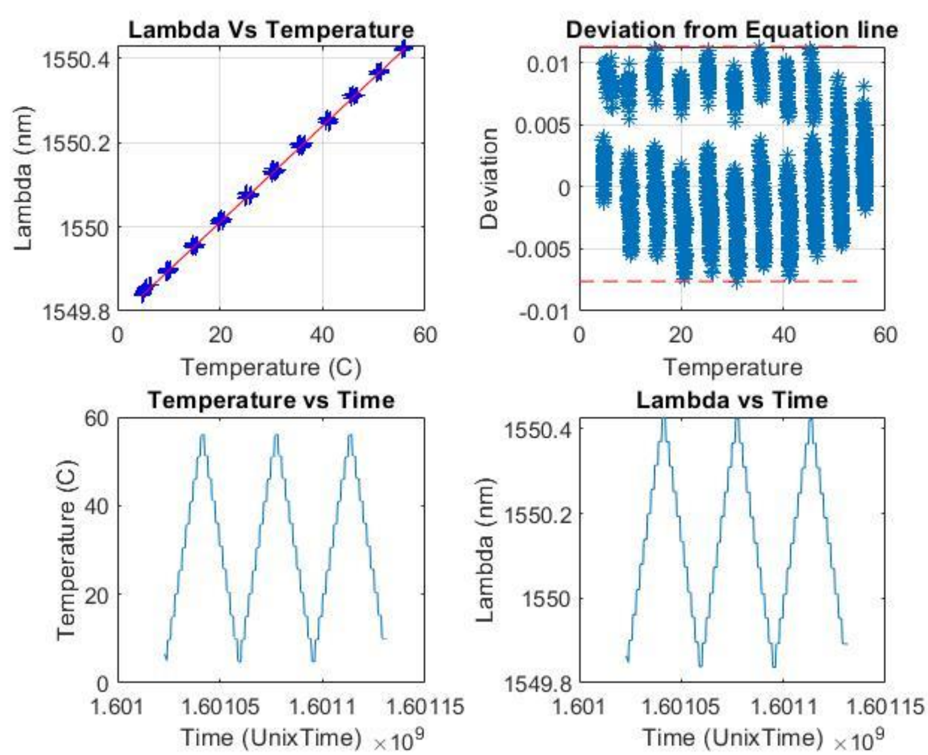
HF-CT2_11_3



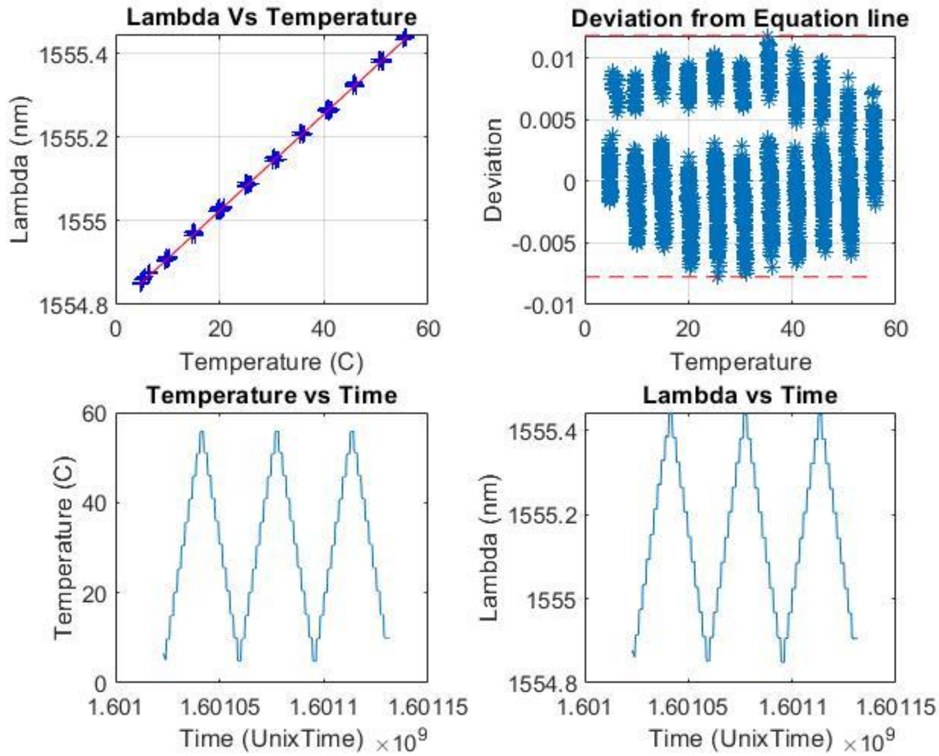
HF-CT2_11_4



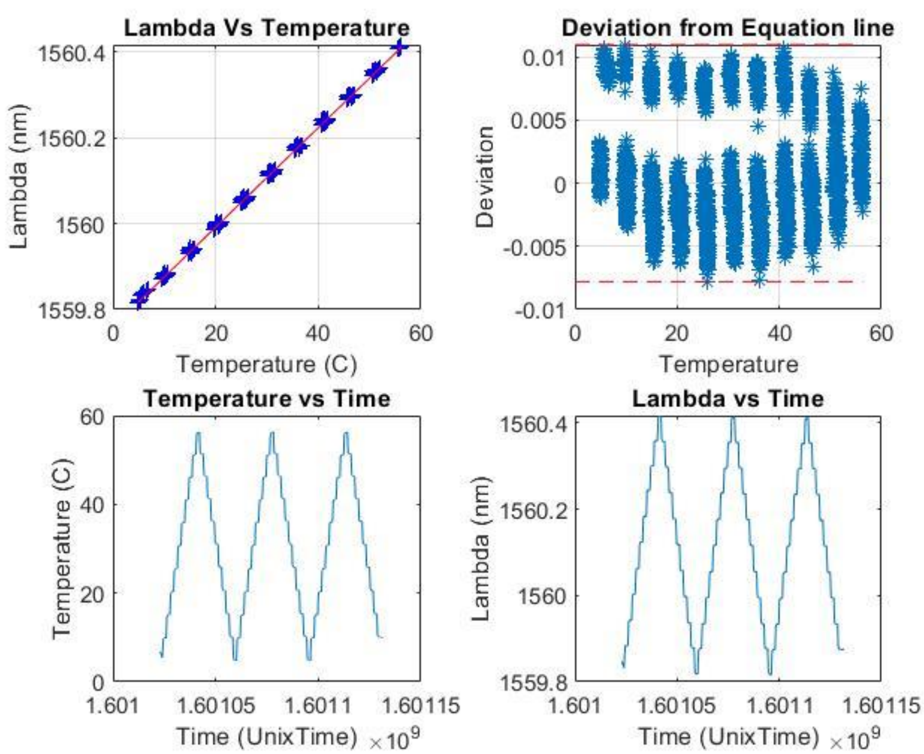
HF-CT2_11_5



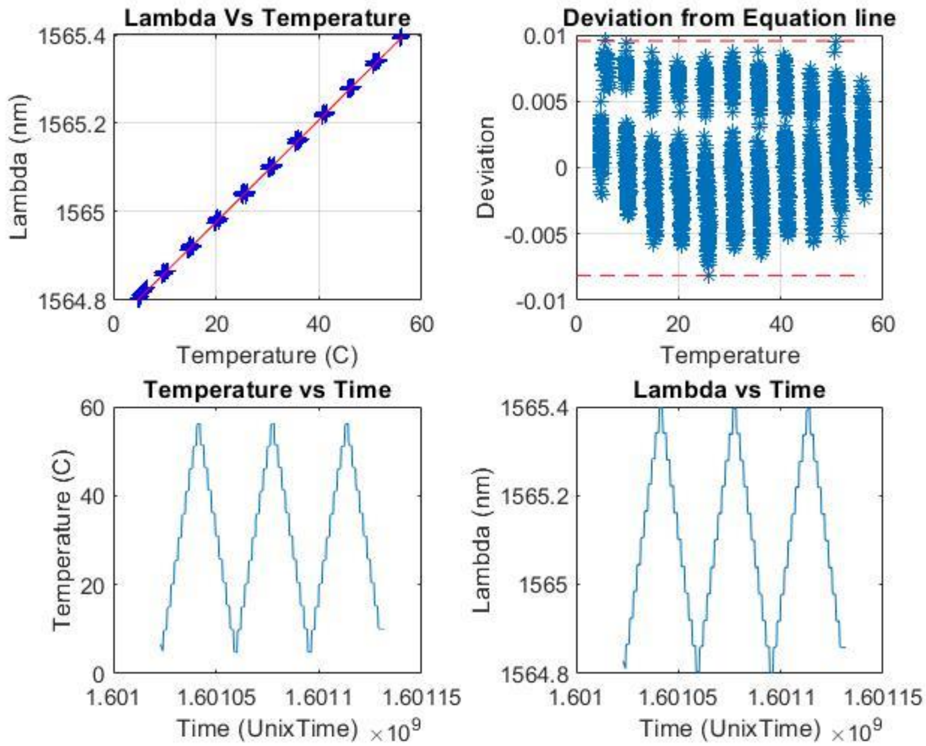
HF-CT2_11_6



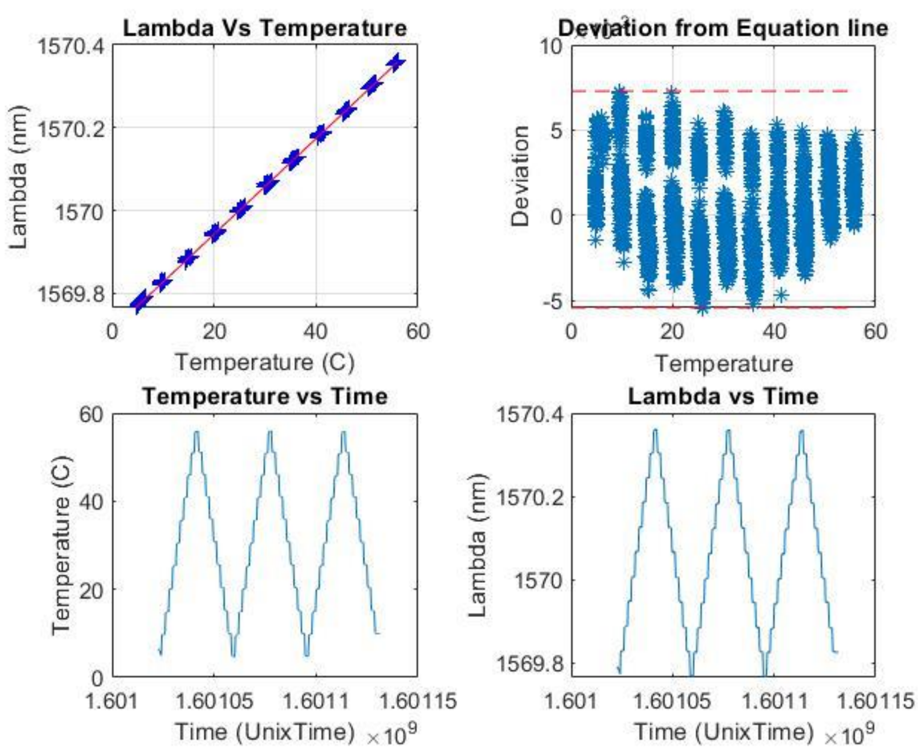
HF-CT2_11_7



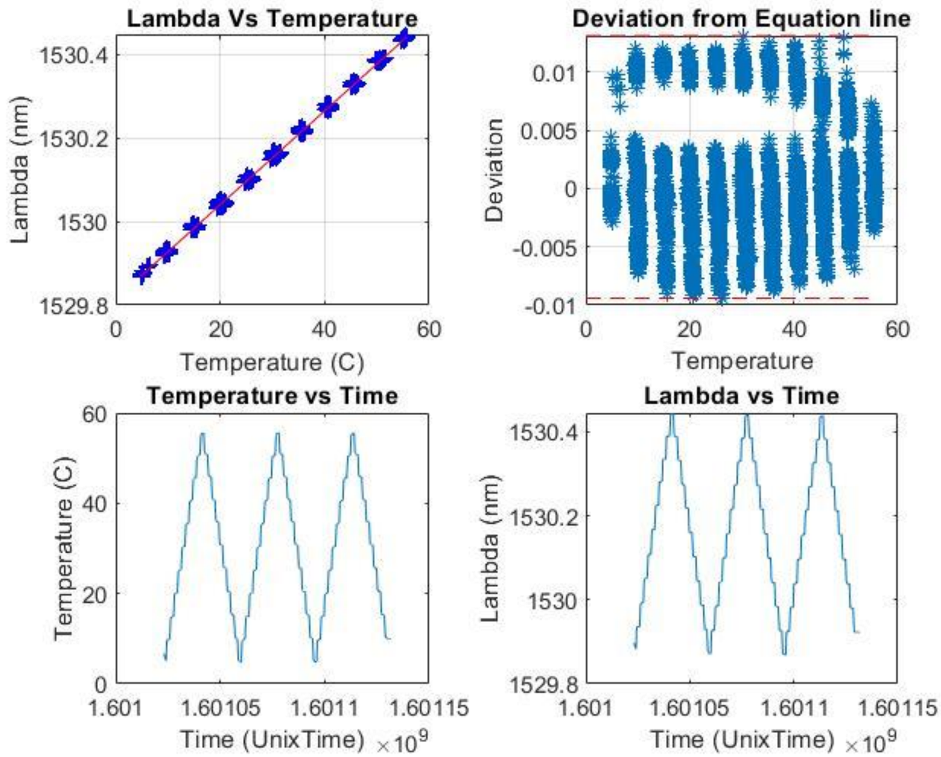
HF-CT2_11_8



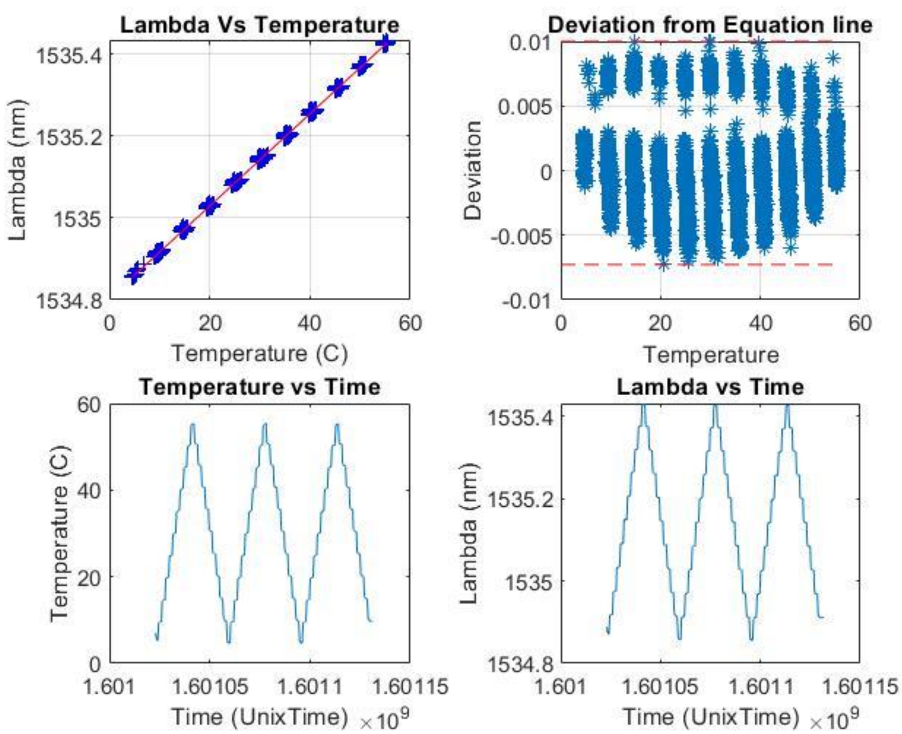
HF-CT2_11_9



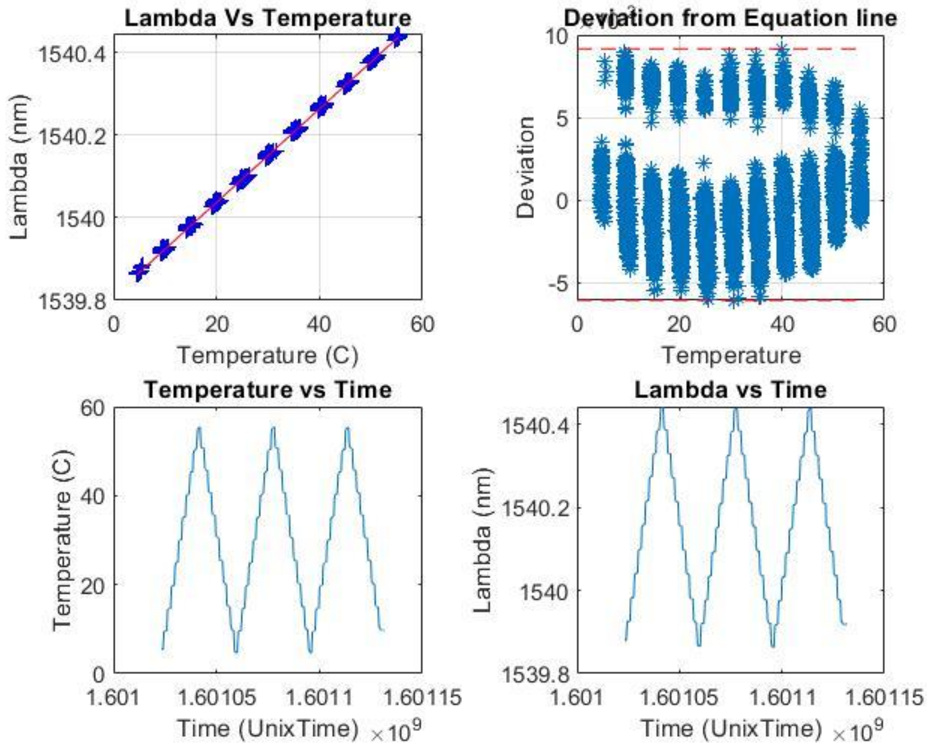
HF-CT2_12_1



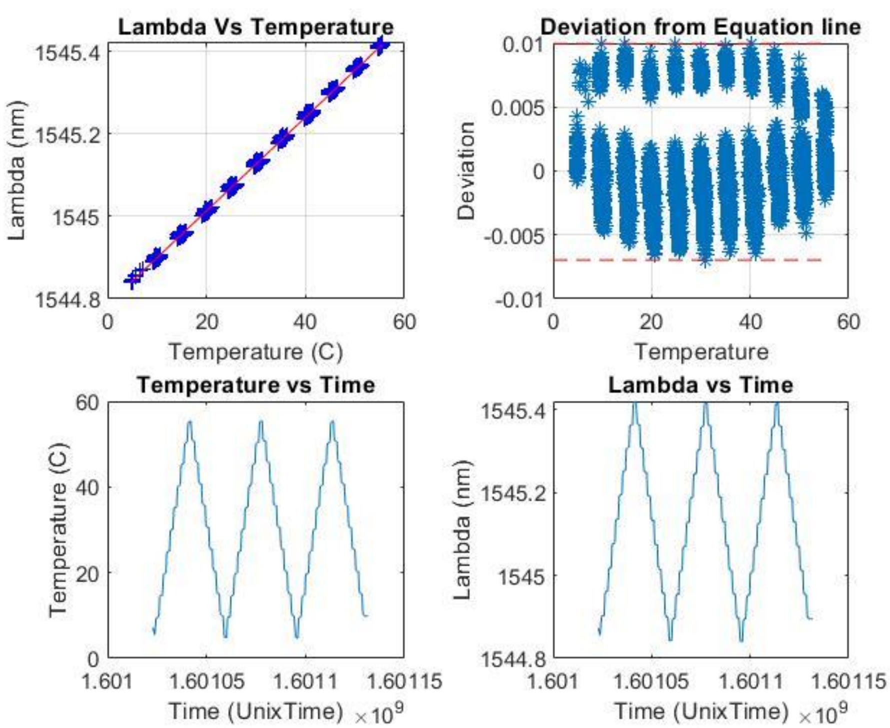
HF-CT2_12_2



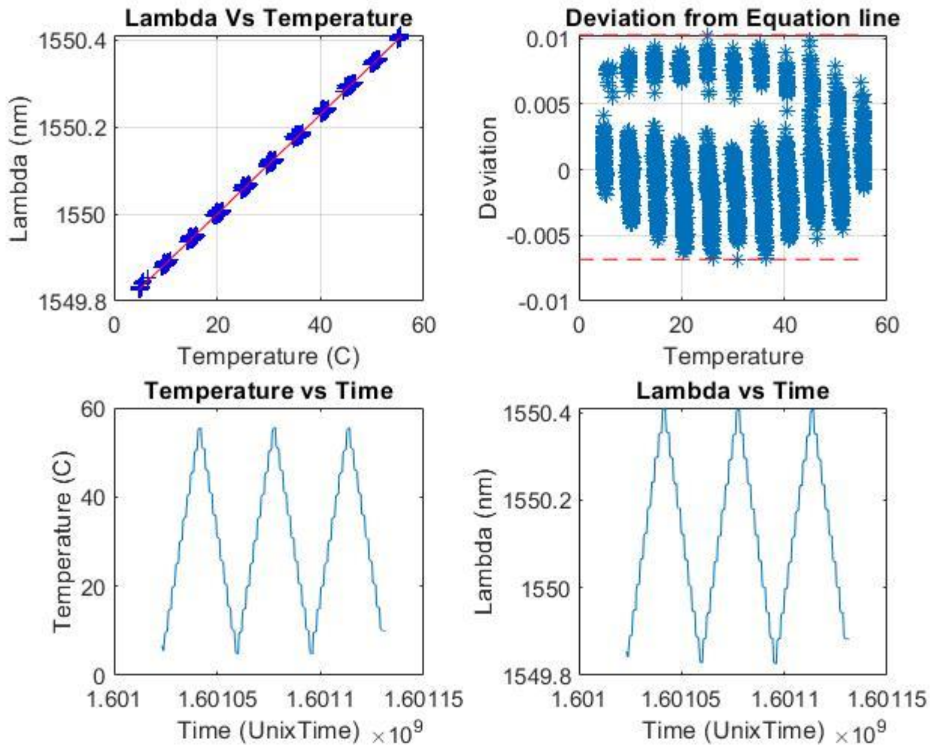
HF-CT2_12_3



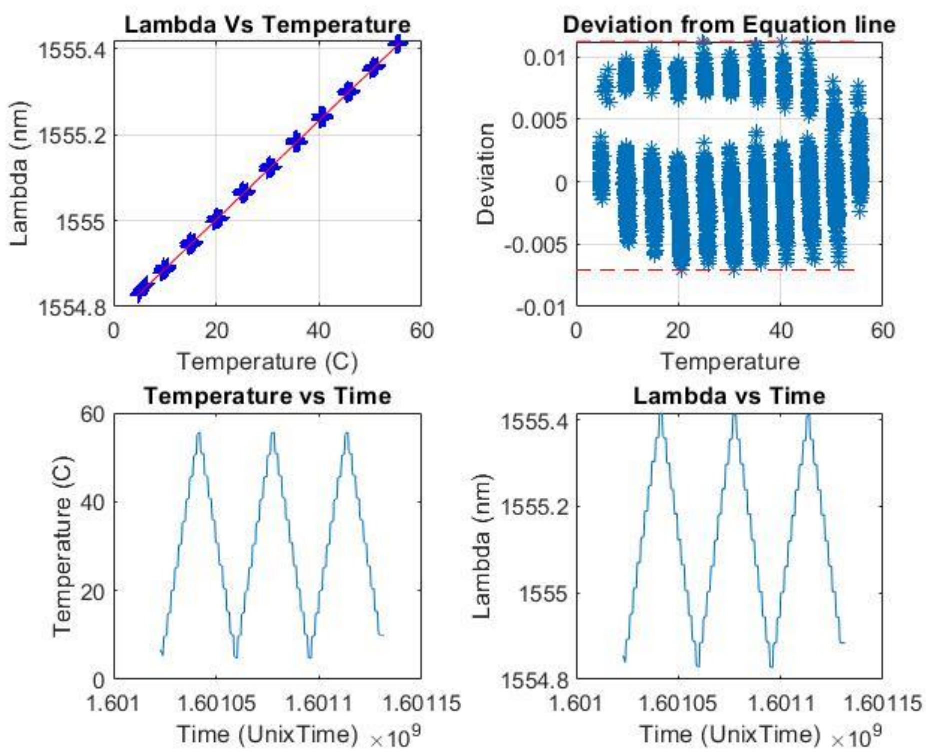
HF-CT2_12_4



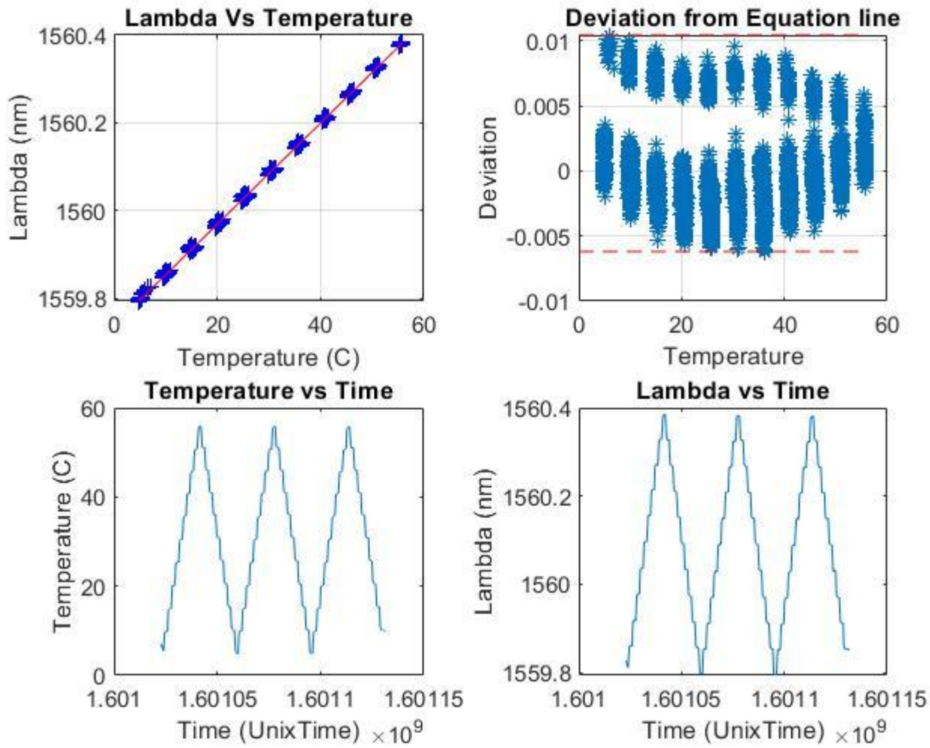
HF-CT2_12_5



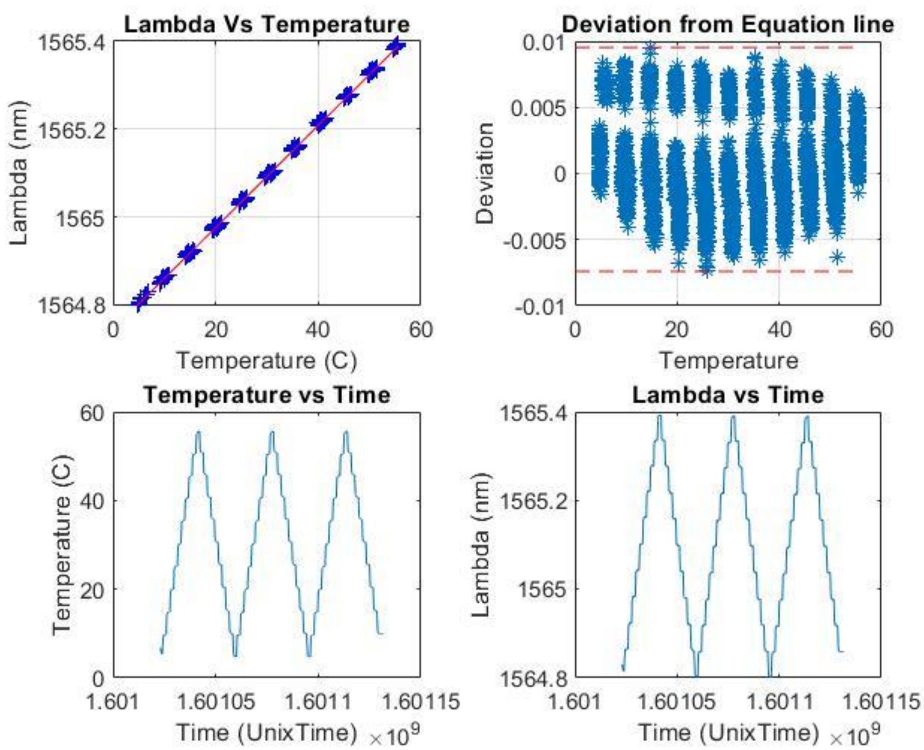
HF-CT2_12_6



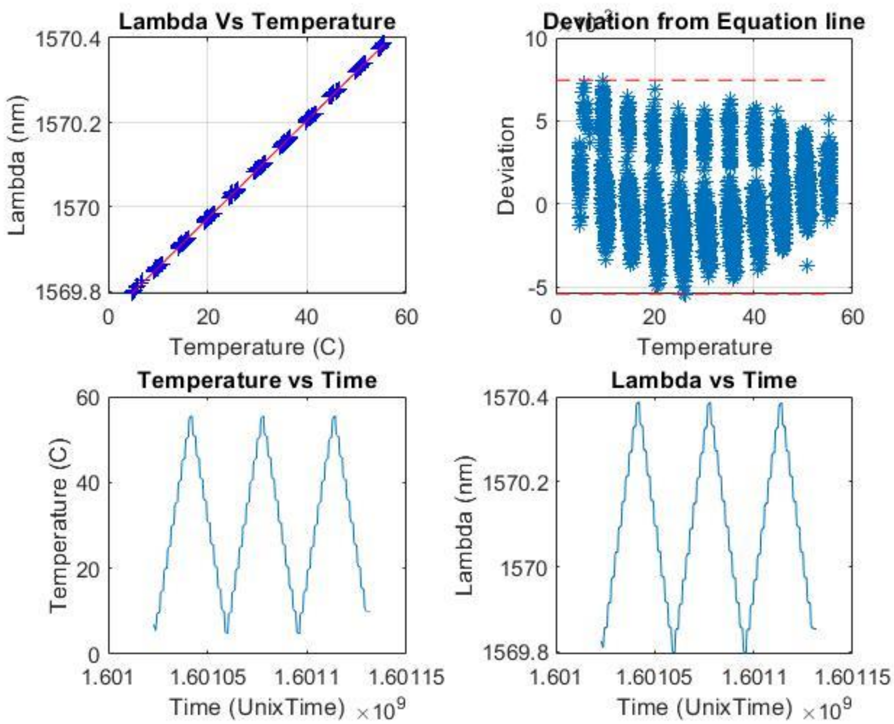
HF-CT2_12_7



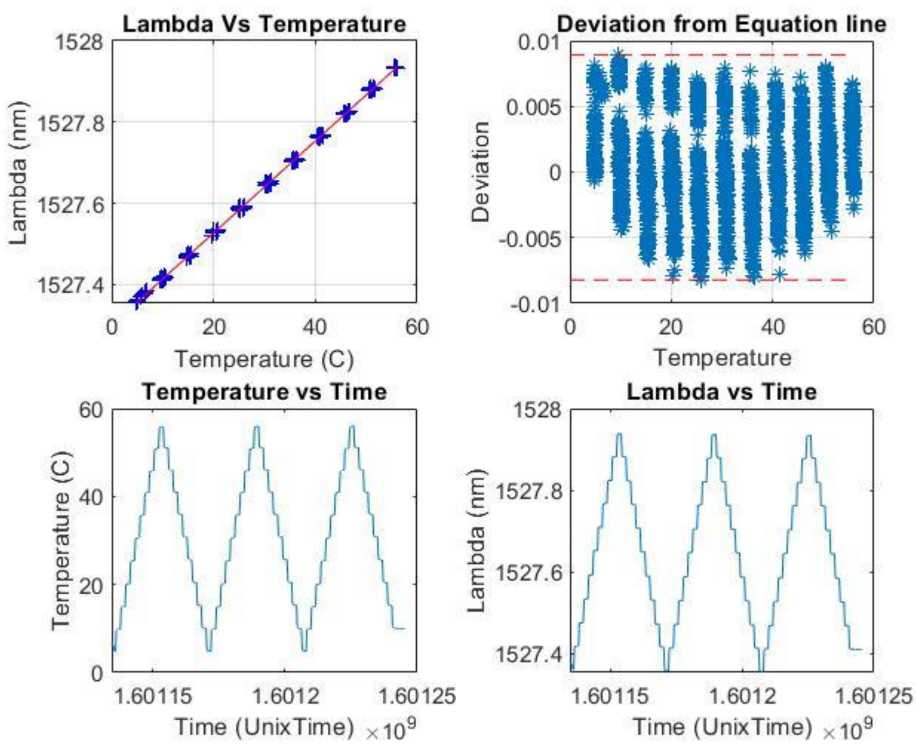
HF-CT2_12_8



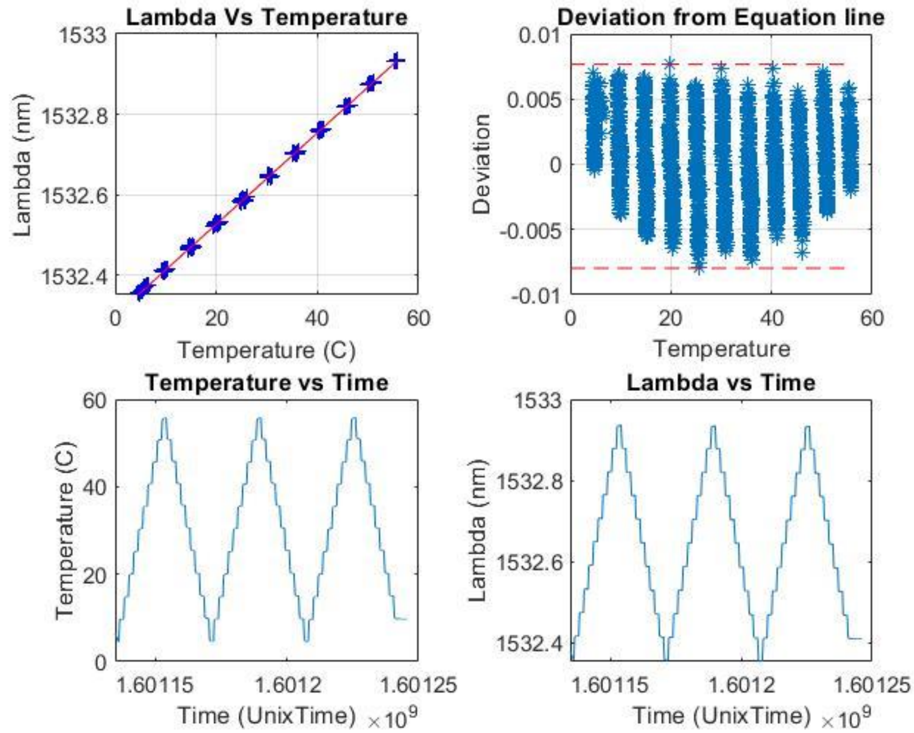
HF-CT2_12_9



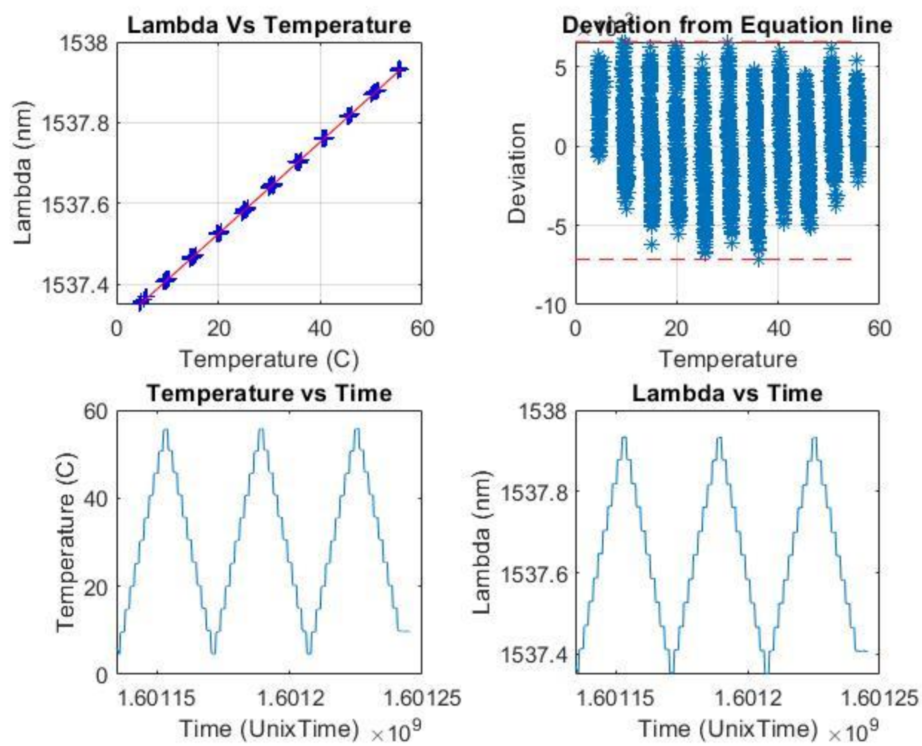
HF-CT2_21_1



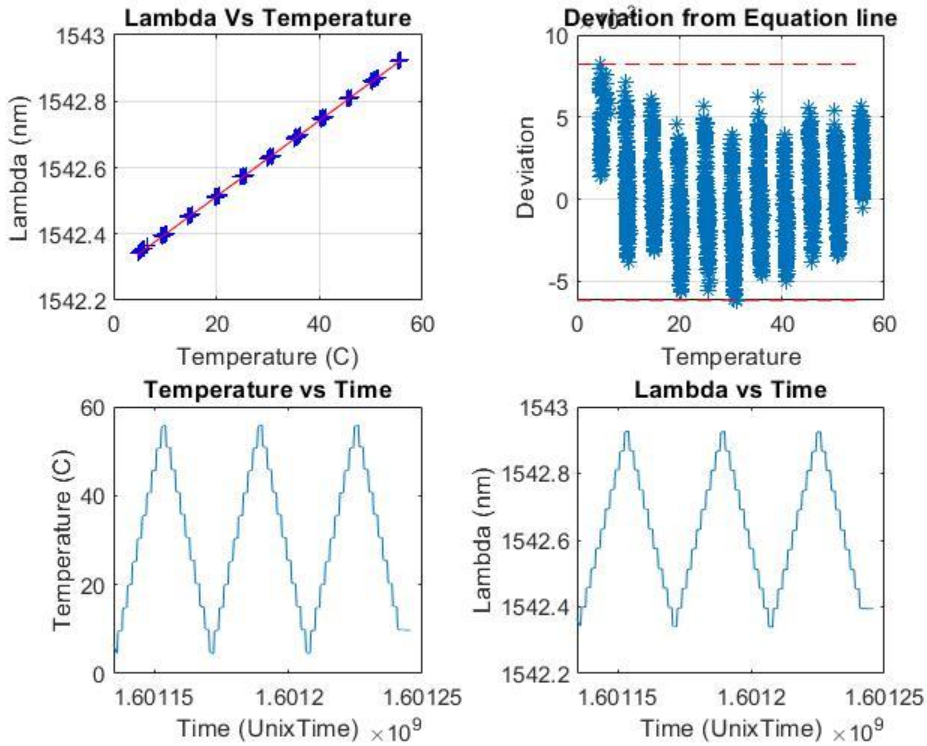
HF-CT2_21_2



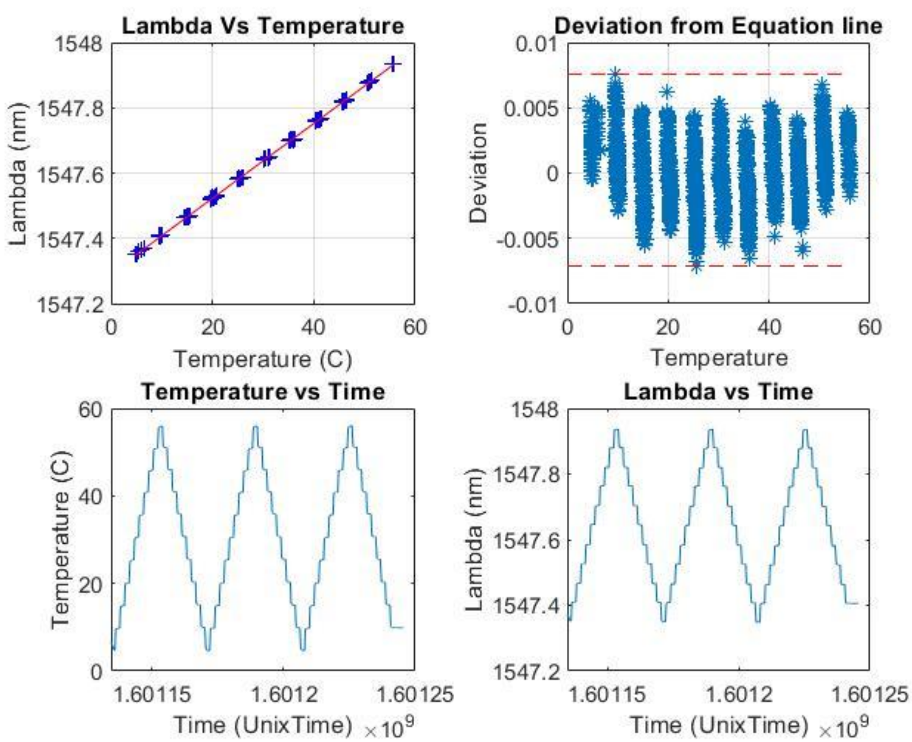
HF-CT2_21_3



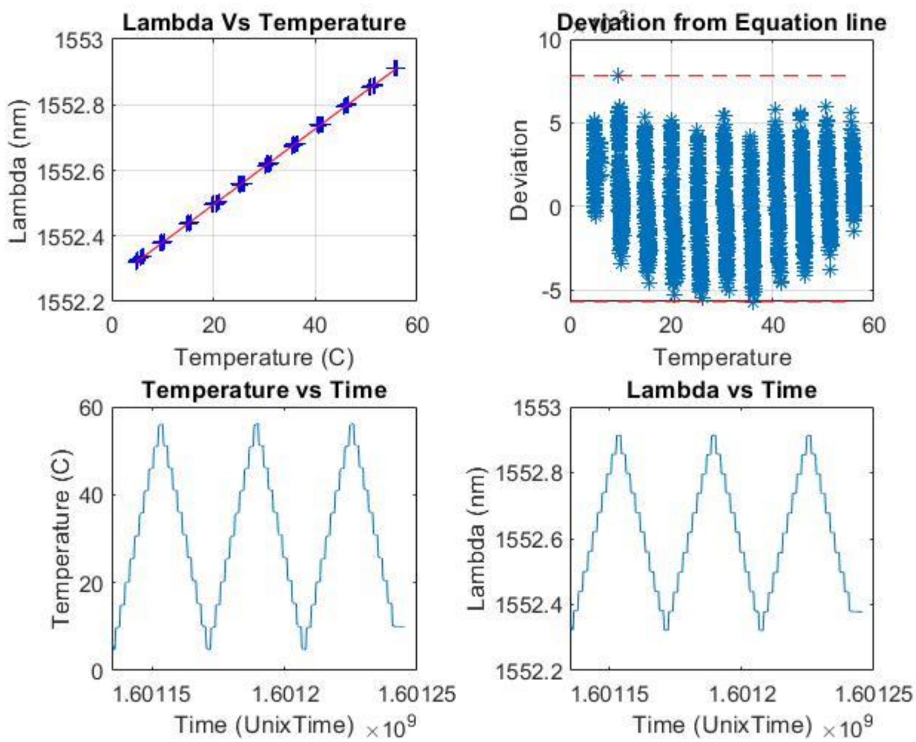
HF-CT2_21_4



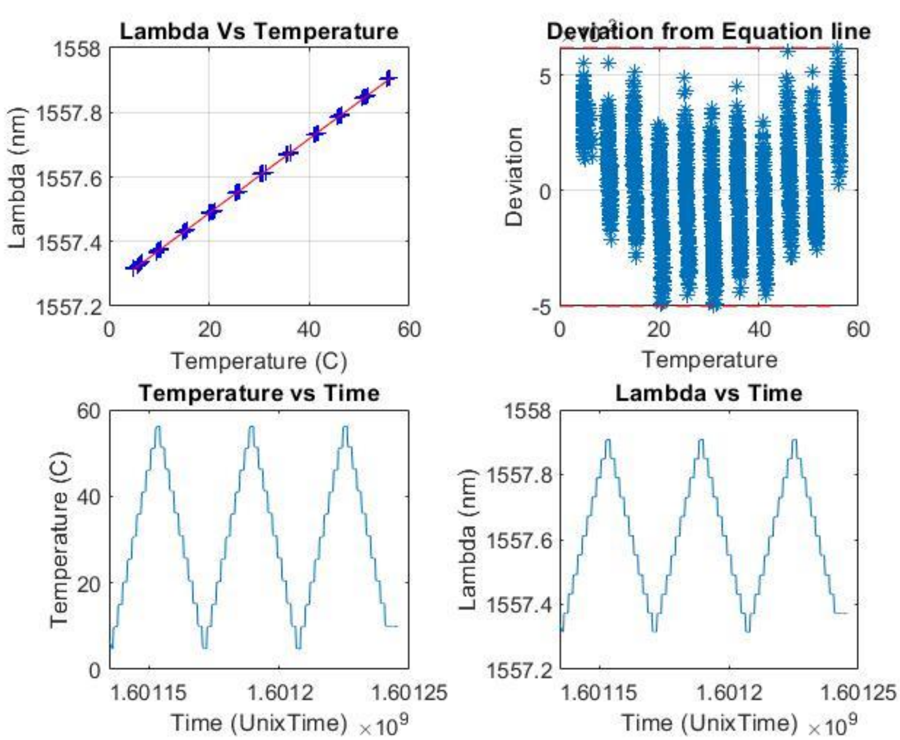
HF-CT2_21_5



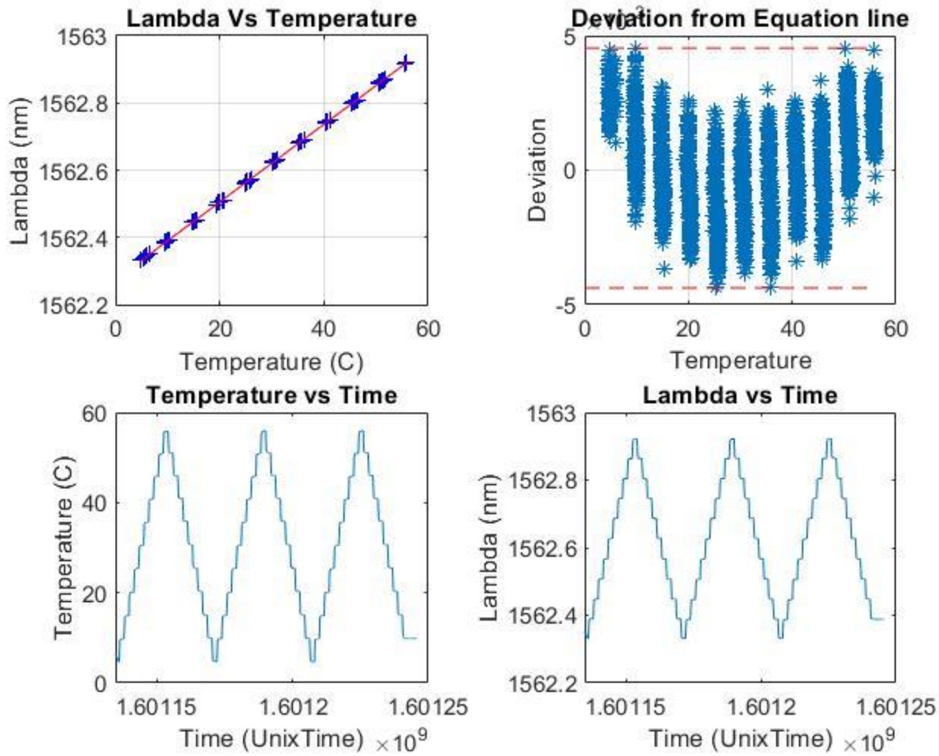
HF-CT2_21_6



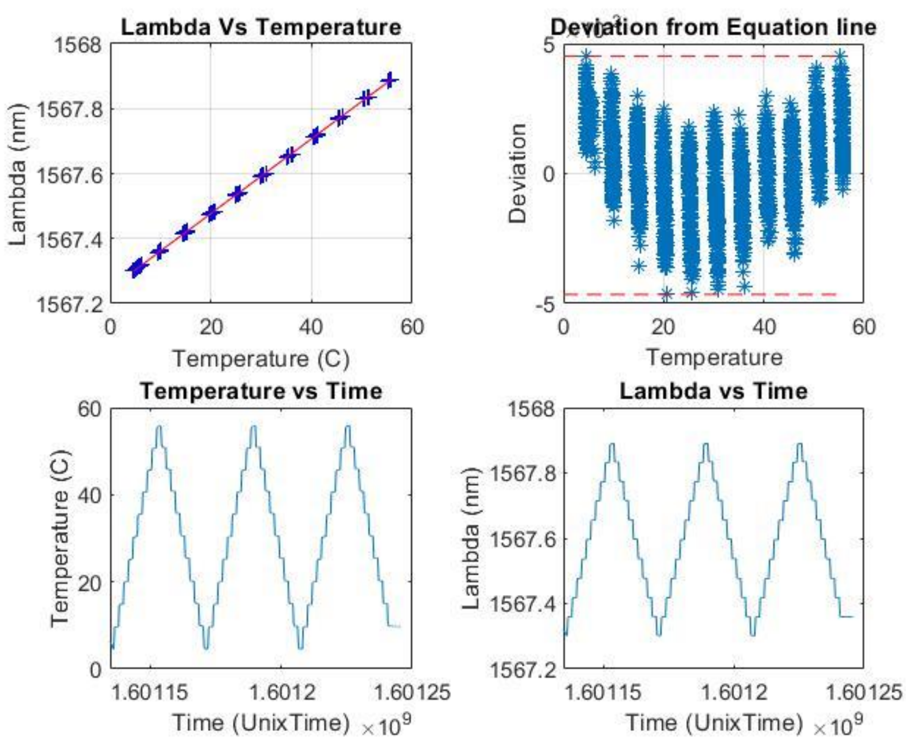
HF-CT2_21_7



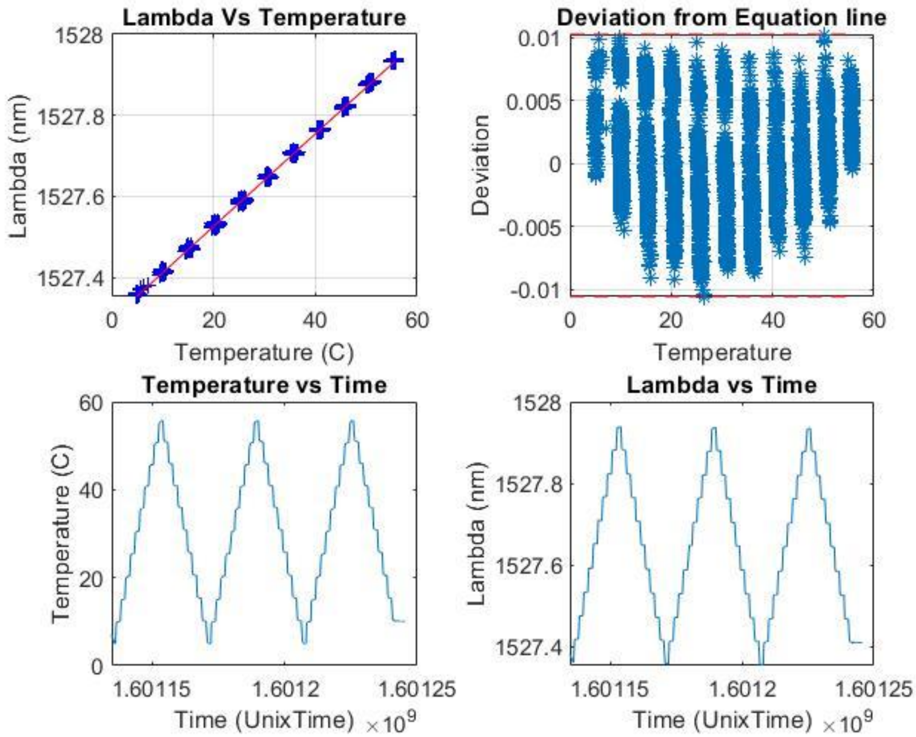
HF-CT2_21_8



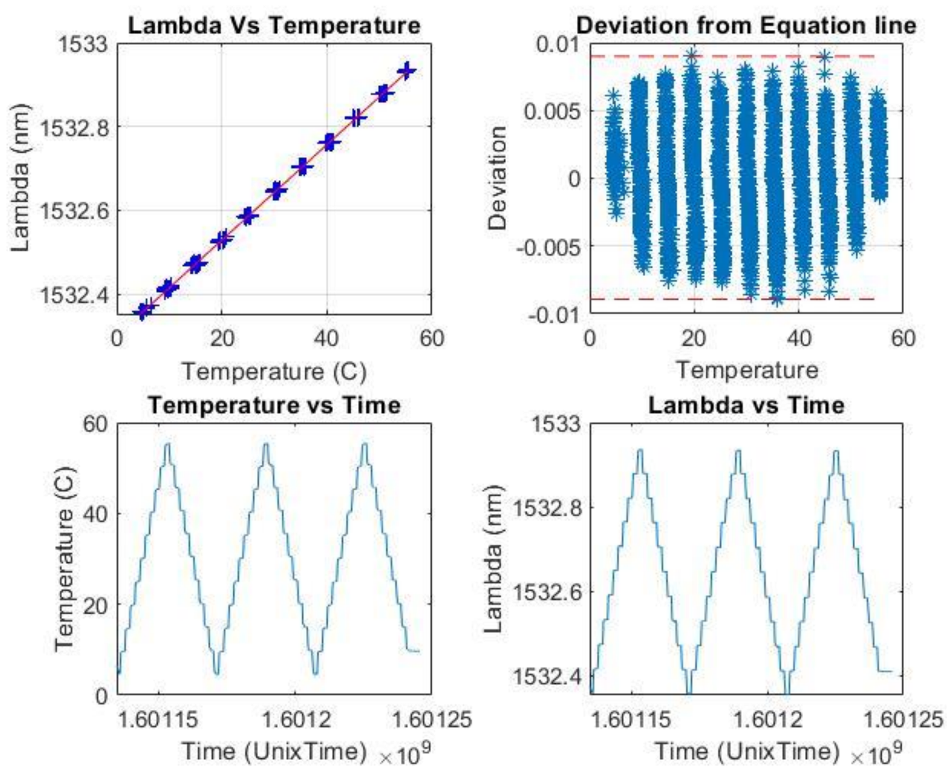
HF-CT2_21_9



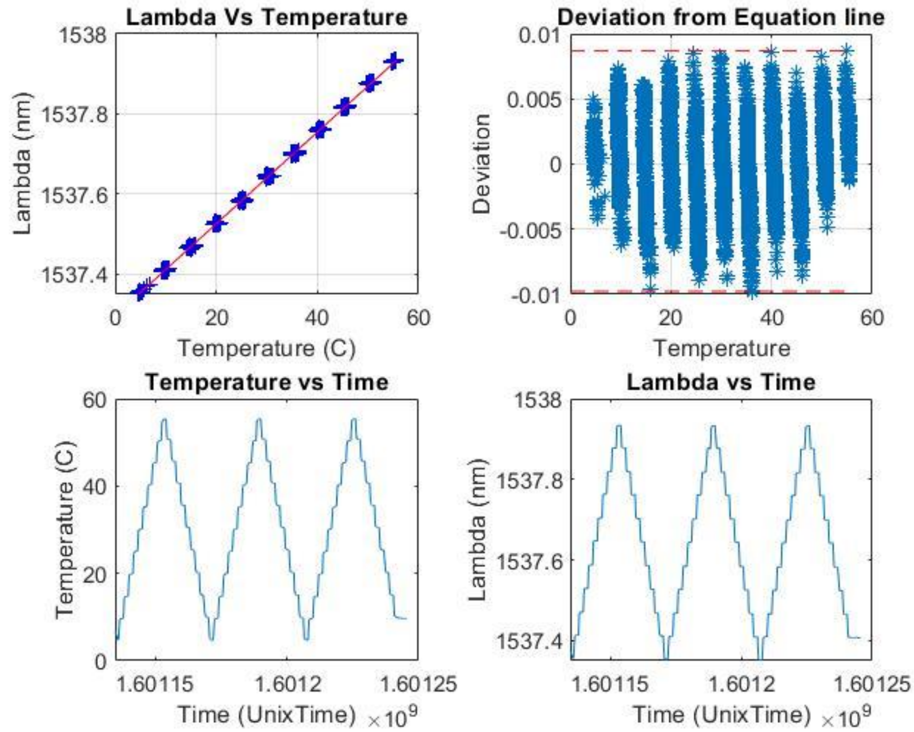
HF-CT2_22_1



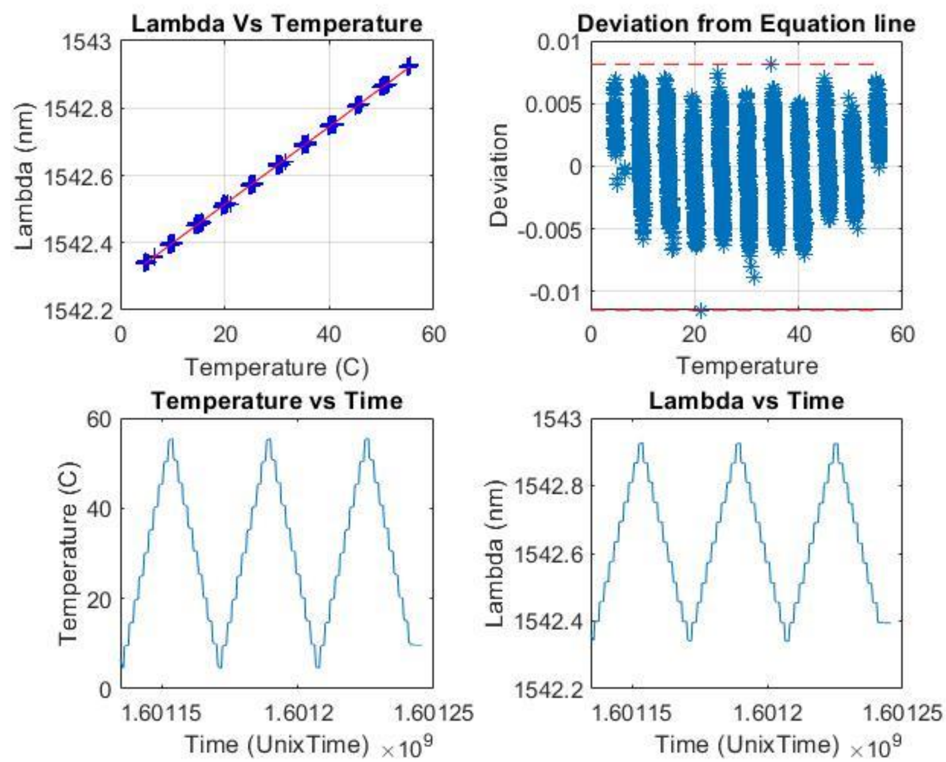
HF-CT2_22_2



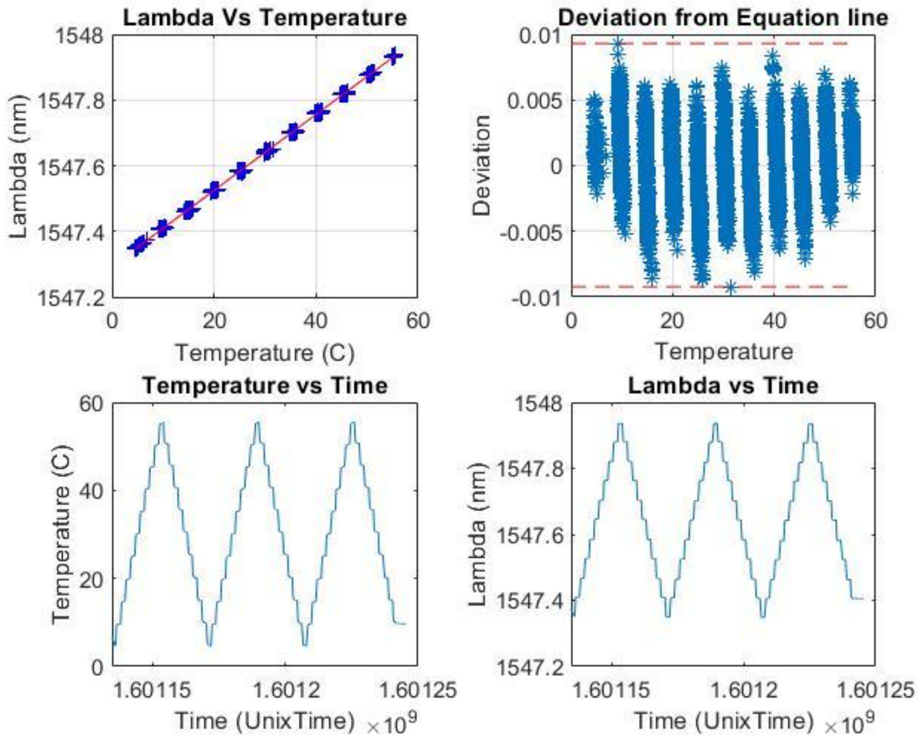
HF-CT2_22_3



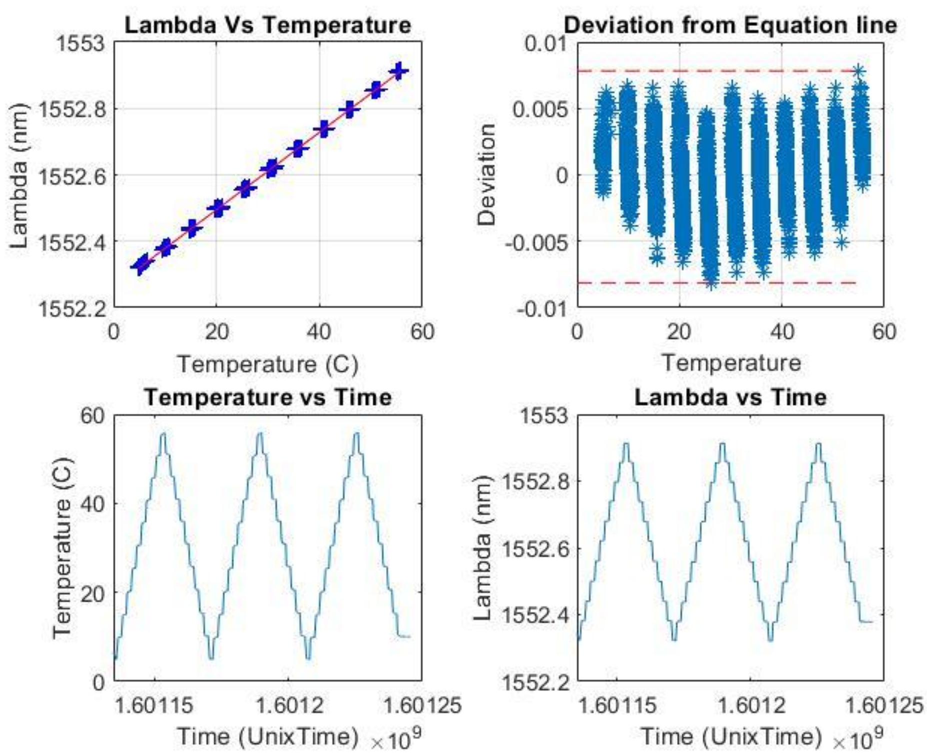
HF-CT2_22_4



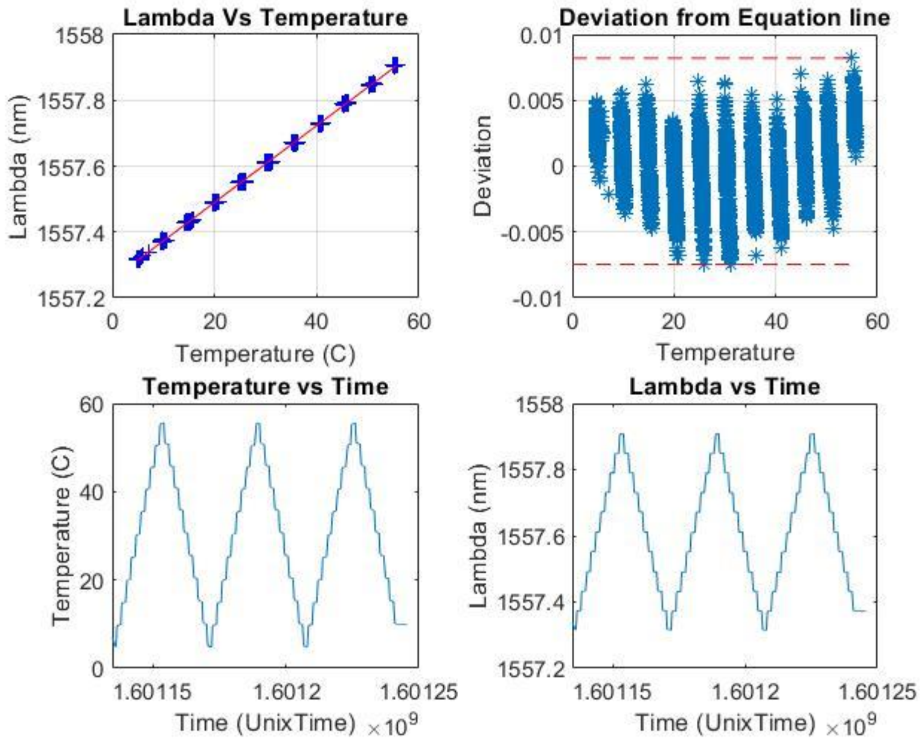
HF-CT2_22_5



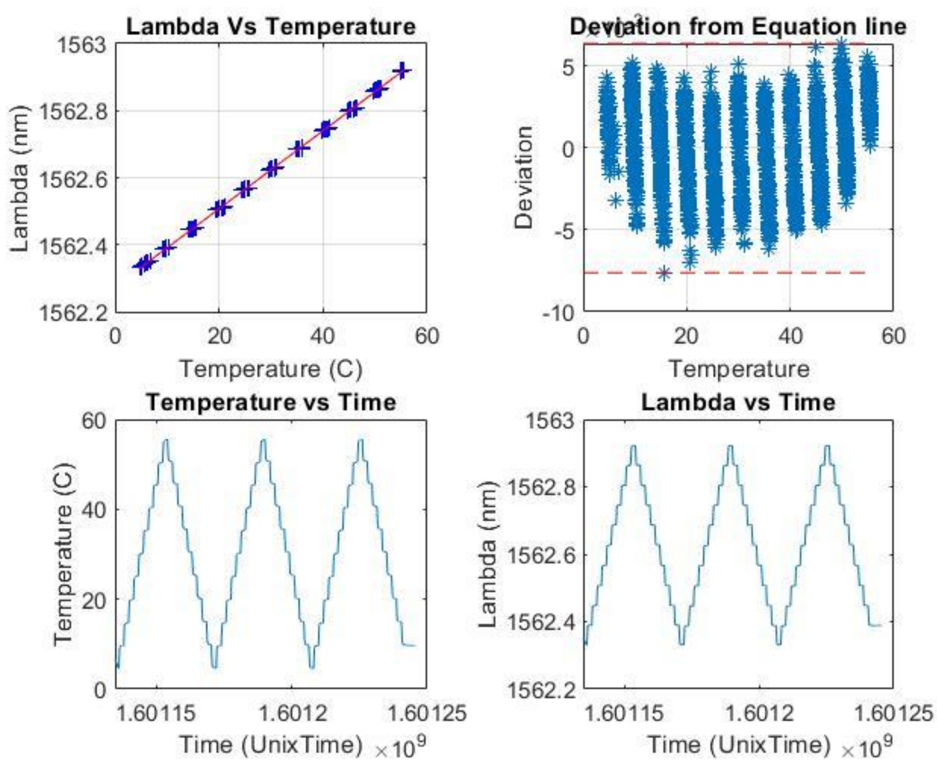
HF-CT2_22_6



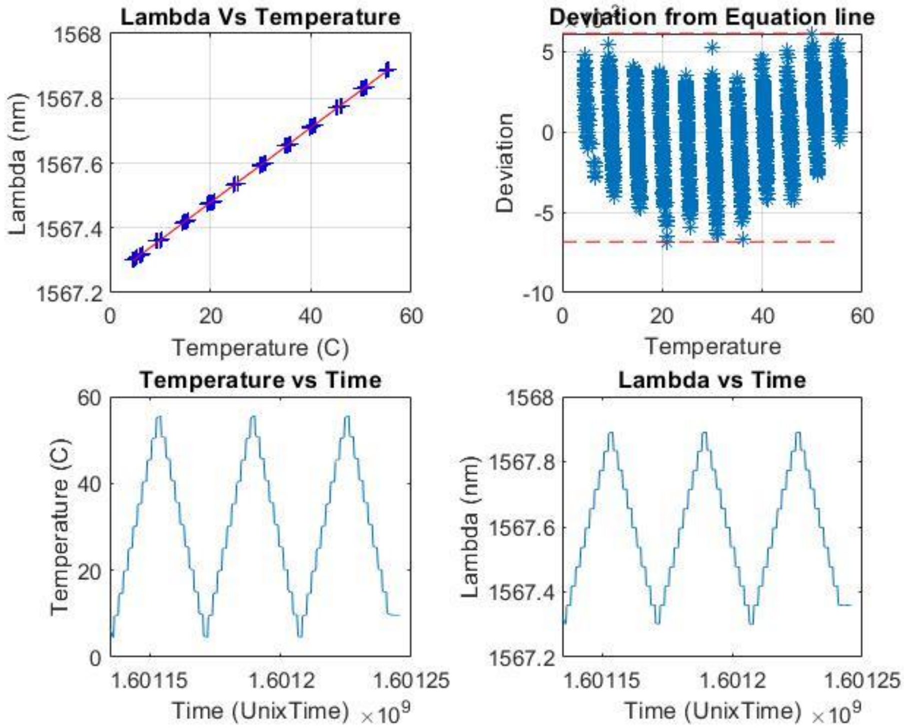
HF-CT2_22_7



HF-CT2_22_8

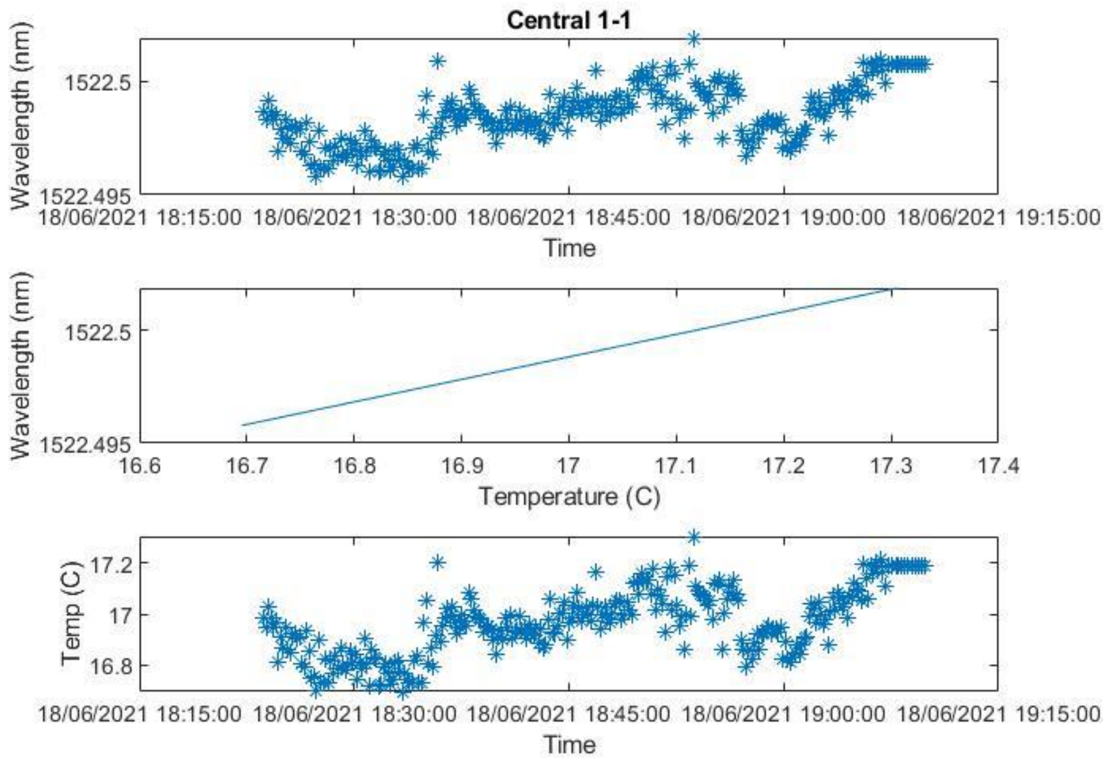


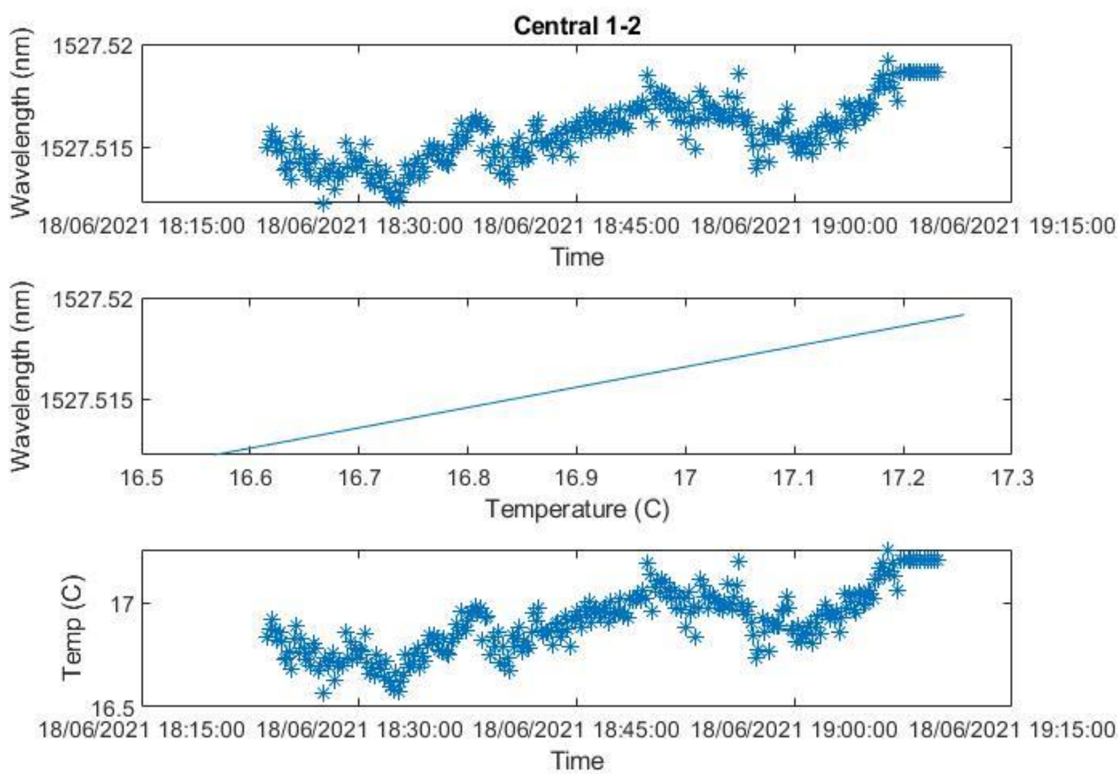
HF-CT2_22_9

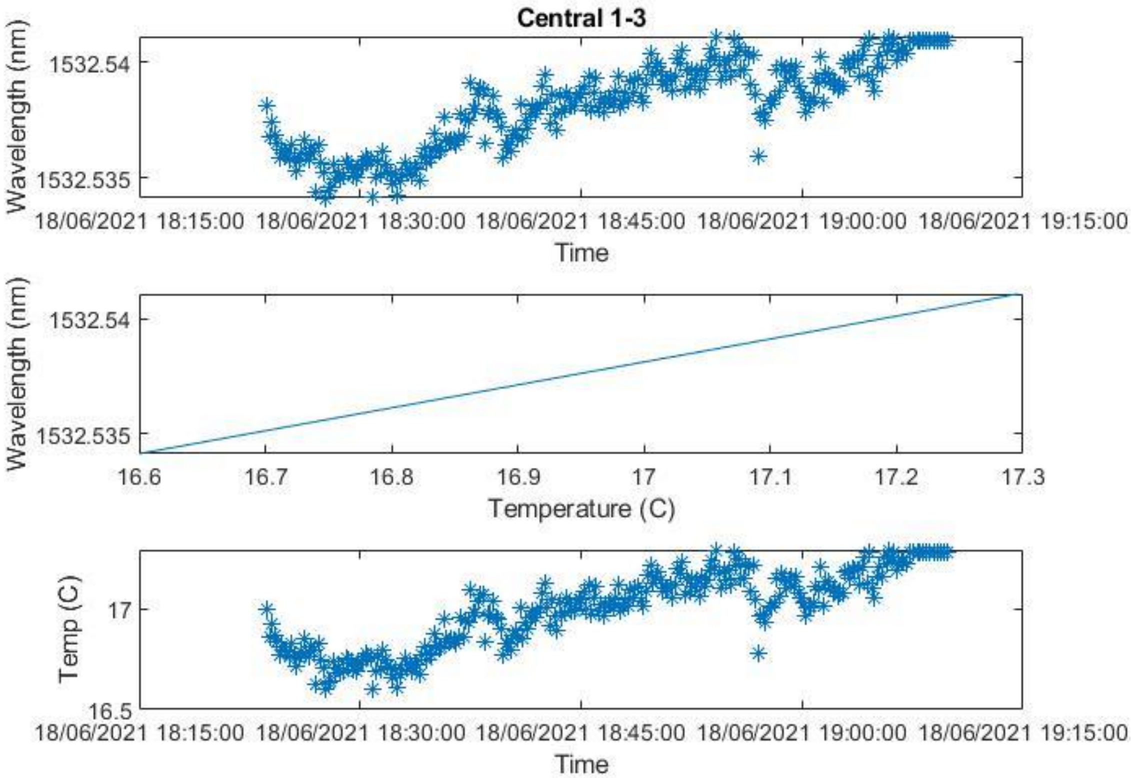


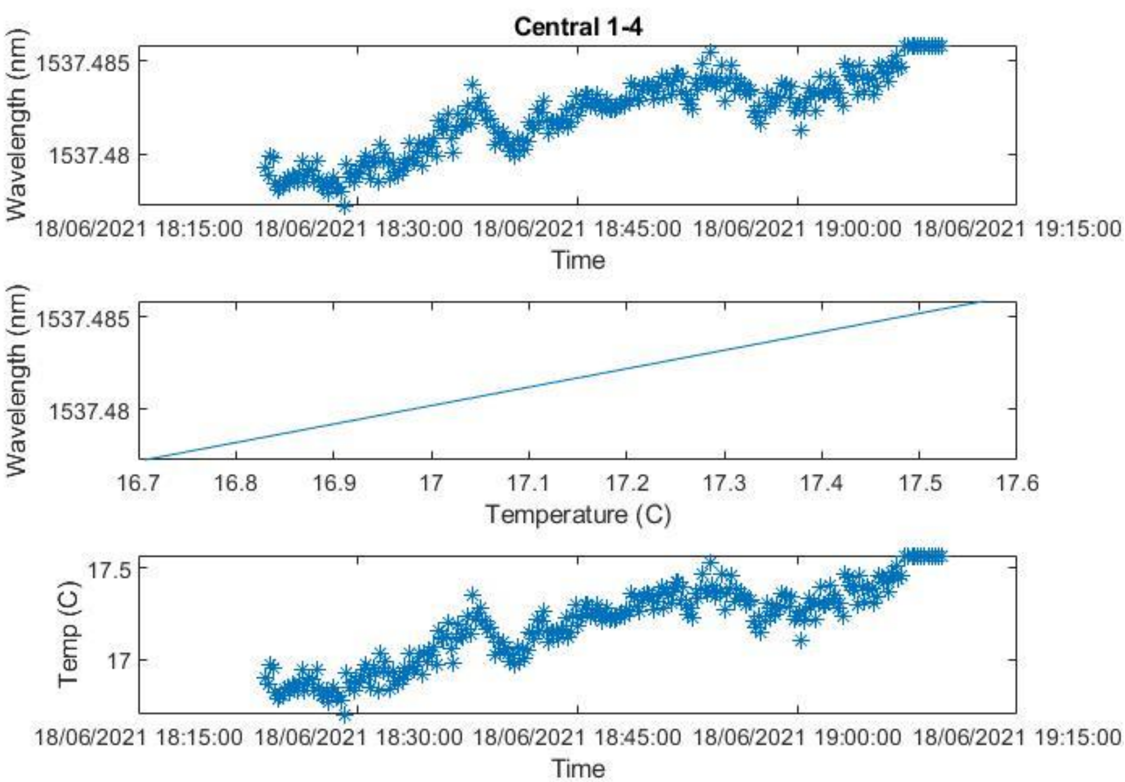
Lambda Vs Temperature
Lambda (nm)
Temperature (C)
Deviation from Equation line
Deviation
Temperature
Temperature vs Time
Temperature (C)
Time (UnixTime) ×10^9
Lambda vs Time
Lambda (nm)
Time (UnixTime) ×10^9

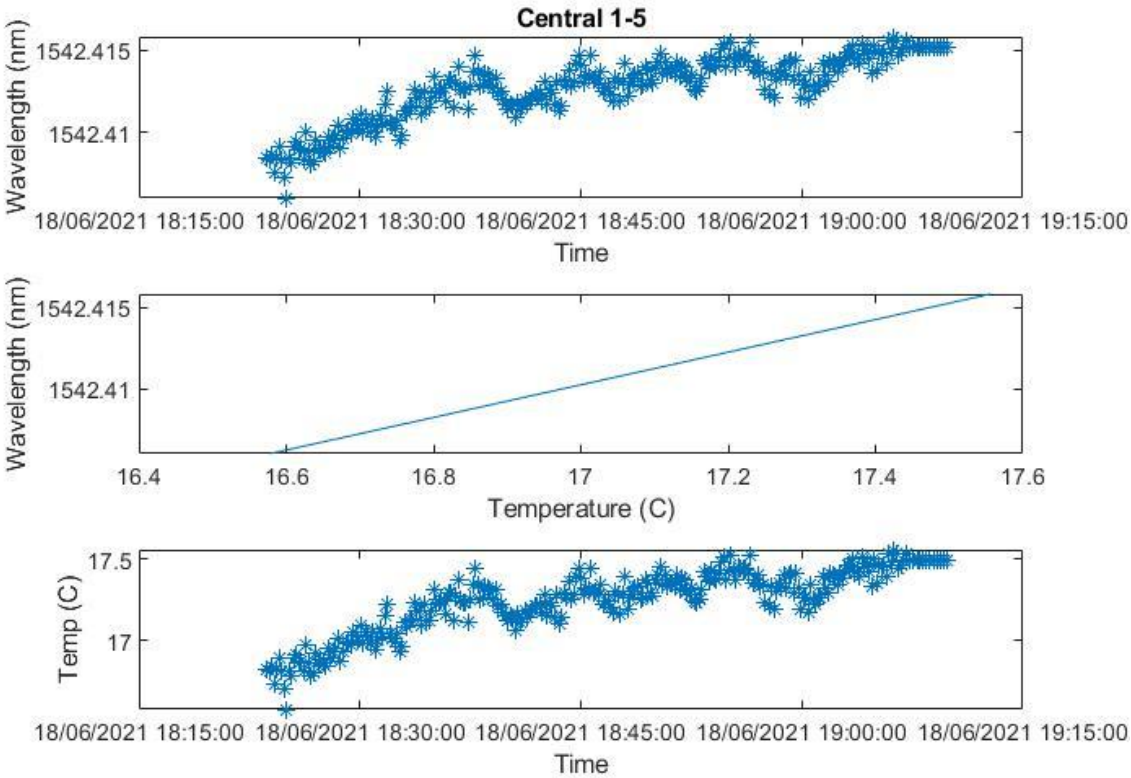
9.2 Central Beam Pipe Recalibration Plots

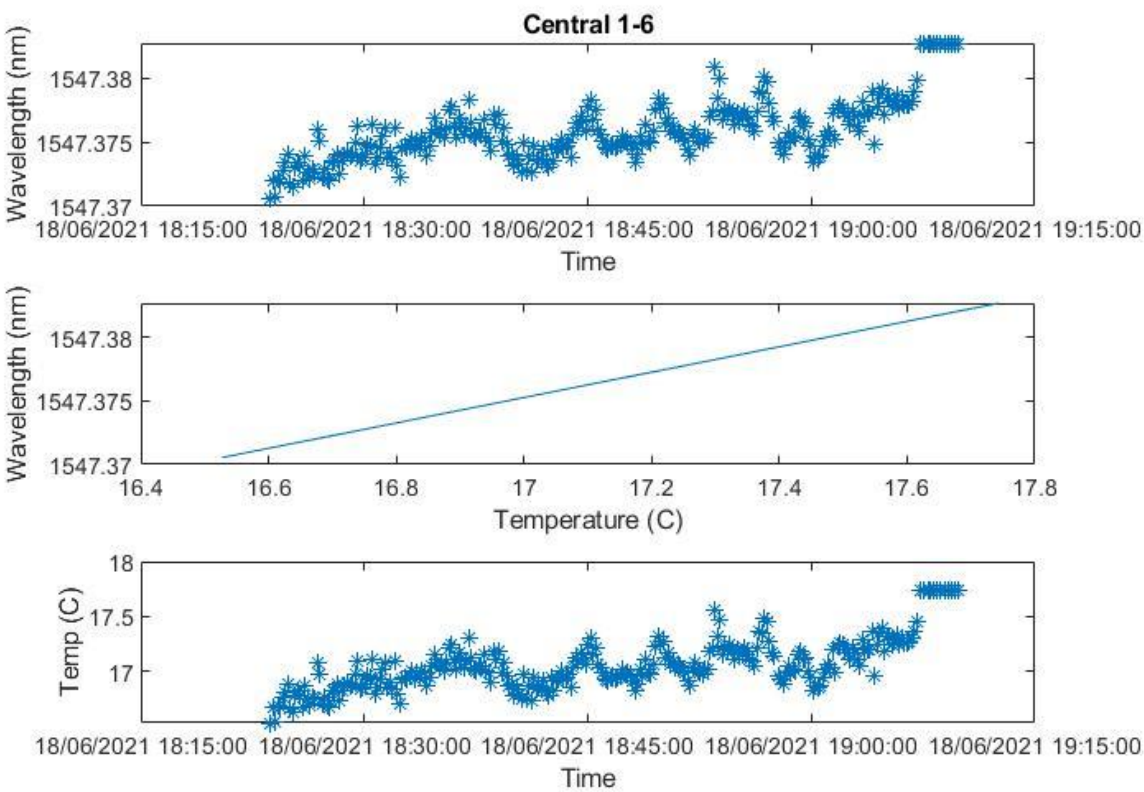


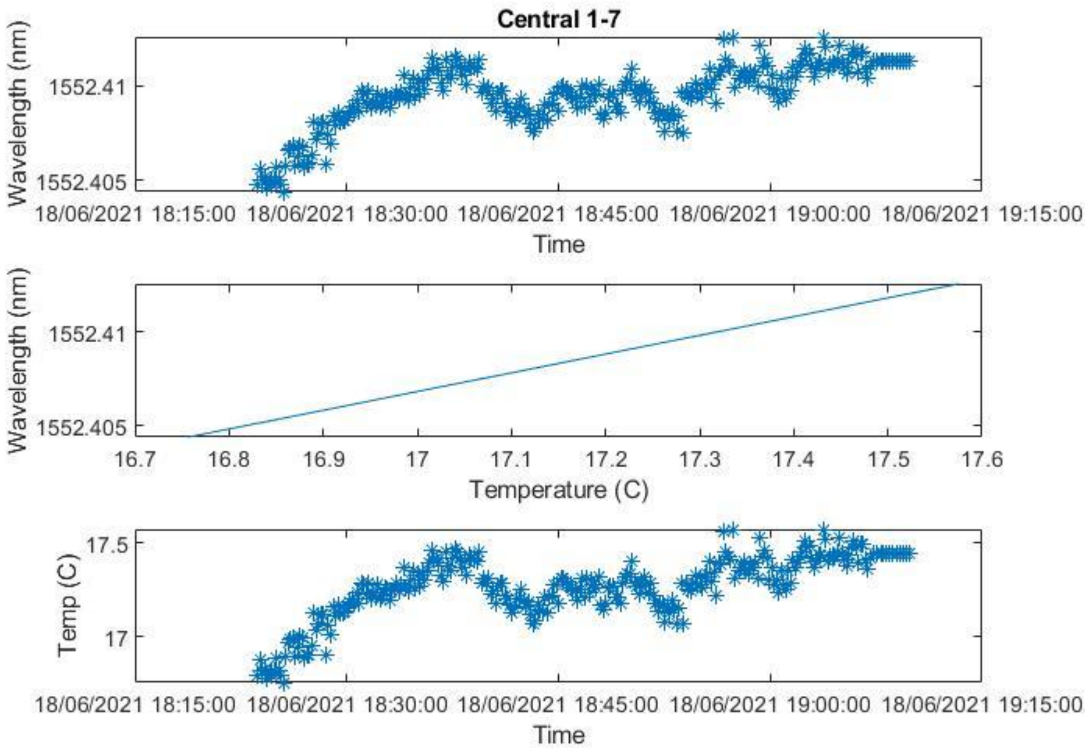


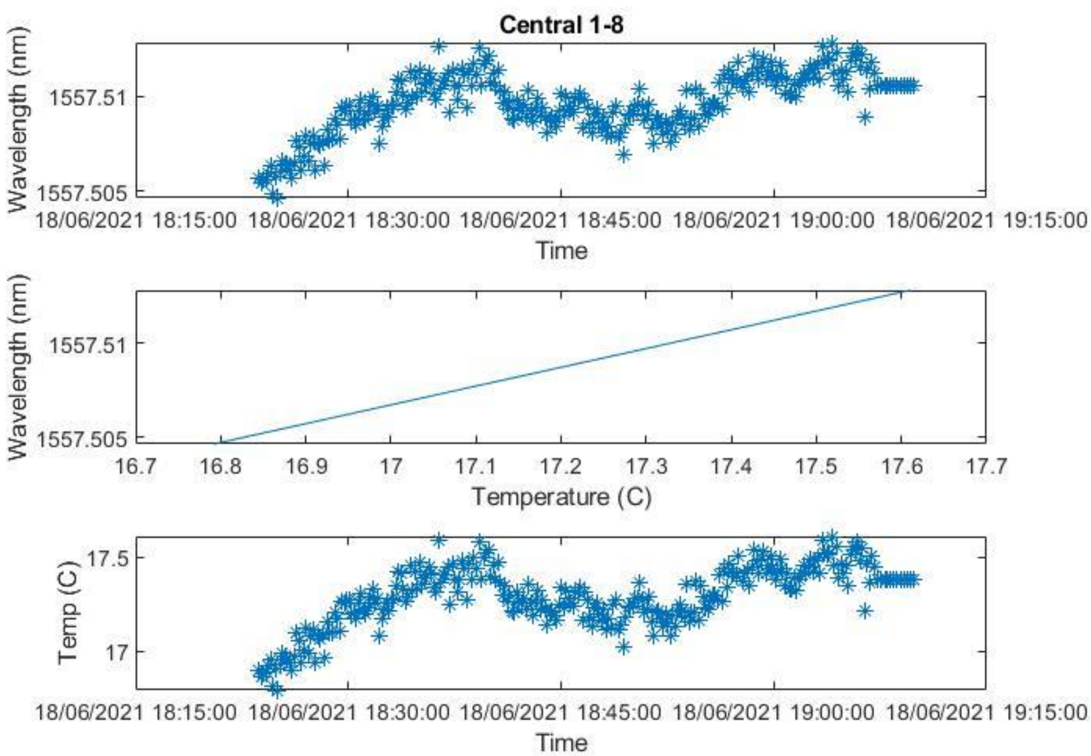

Central 1-3
Wavelength (nm)
1532.54
1532.535
18/06/2021 18:15:00 18/06/2021 18:30:00 18/06/2021 18:45:00 18/06/2021 19:00:00 18/06/2021 19:15:00
Time
Wavelength (nm)
1532.54
1532.535
16.6 16.7 16.8 16.9 17 17.1 17.2 17.3
Temperature (C)
Temp (C)
17
16.5
18/06/2021 18:15:00 18/06/2021 18:30:00 18/06/2021 18:45:00 18/06/2021 19:00:00 18/06/2021 19:15:00
Time

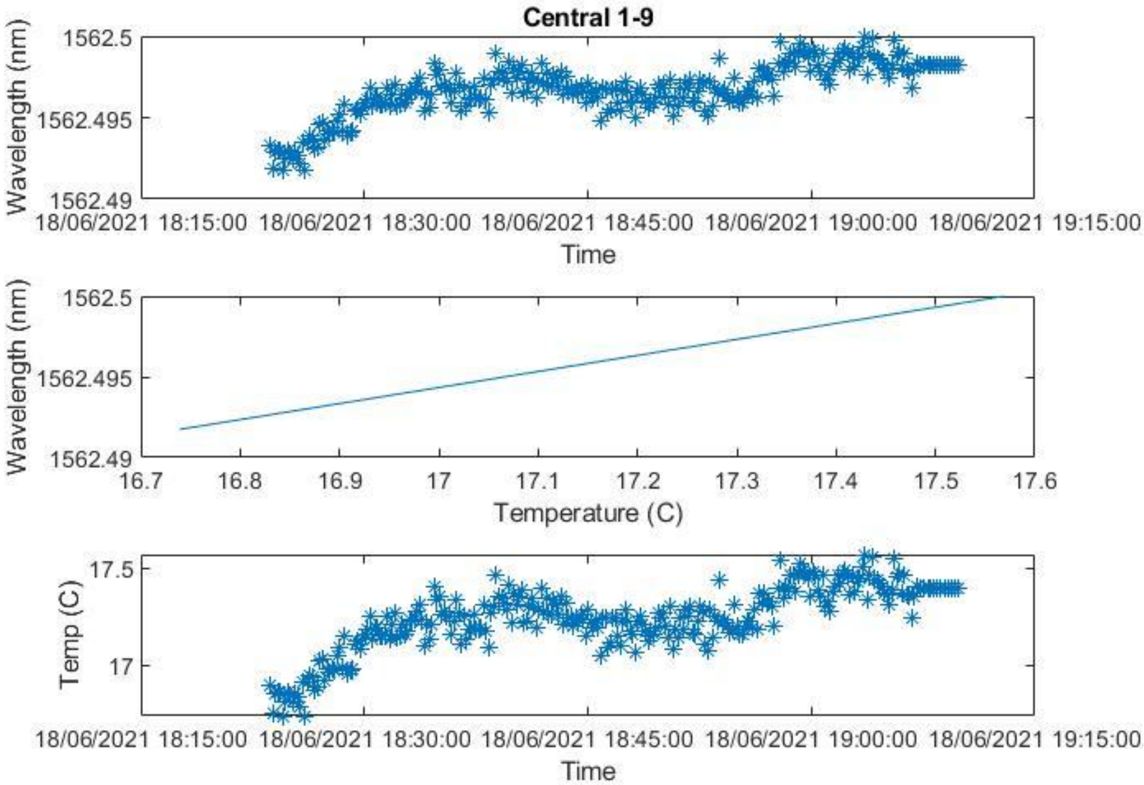

Central 1-4
Wavelength (nm)
1537.485
1537.48
18/06/2021 18:15:00 18/06/2021 18:30:00 18/06/2021 18:45:00 18/06/2021 19:00:00 18/06/2021 19:15:00
Time
Wavelength (nm)
1537.485
1537.48
16.7 16.8 16.9 17 17.1 17.2 17.3 17.4 17.5 17.6
Temperature (C)
Temp (C)
17.5
17
18/06/2021 18:15:00 18/06/2021 18:30:00 18/06/2021 18:45:00 18/06/2021 19:00:00 18/06/2021 19:15:00
Time

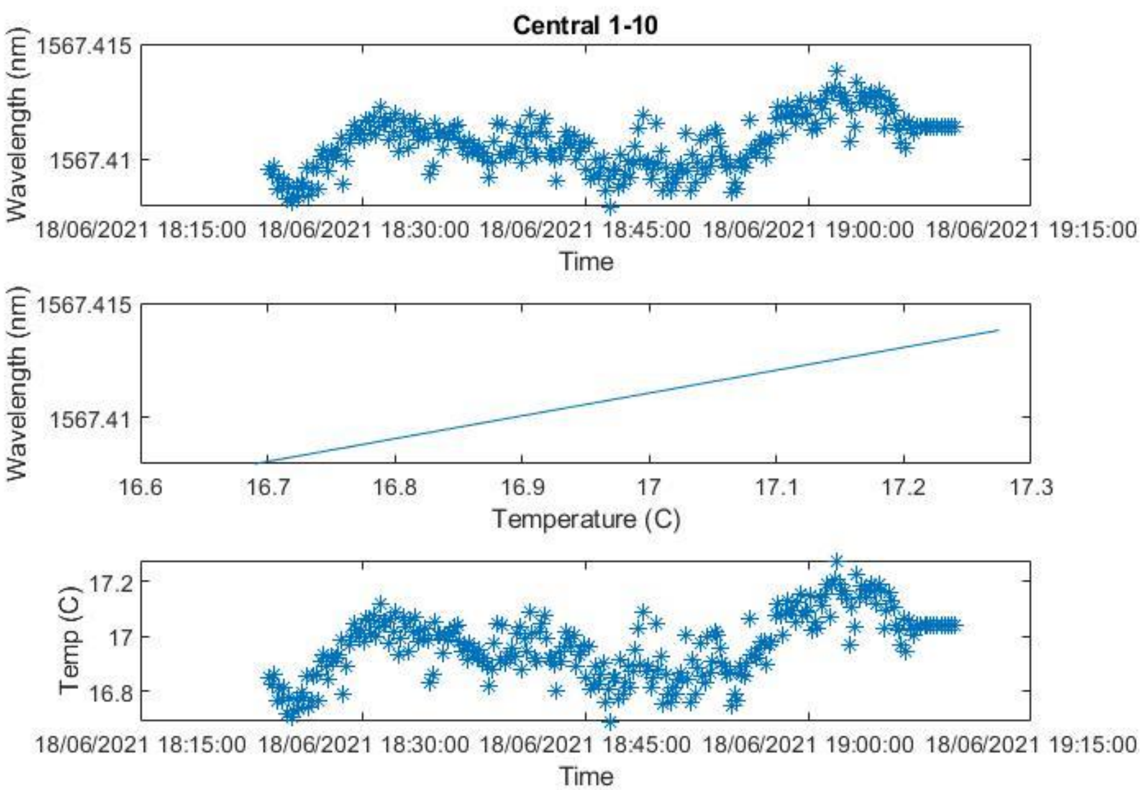

Central 1-5
Wavelength (nm)
1542.415
1542.41
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time
Wavelength (nm)
1542.415
1542.41
16.4
16.6
16.8
17
17.2
17.4
17.6
Temperature (C)
Temp (C)
17.5
17
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time

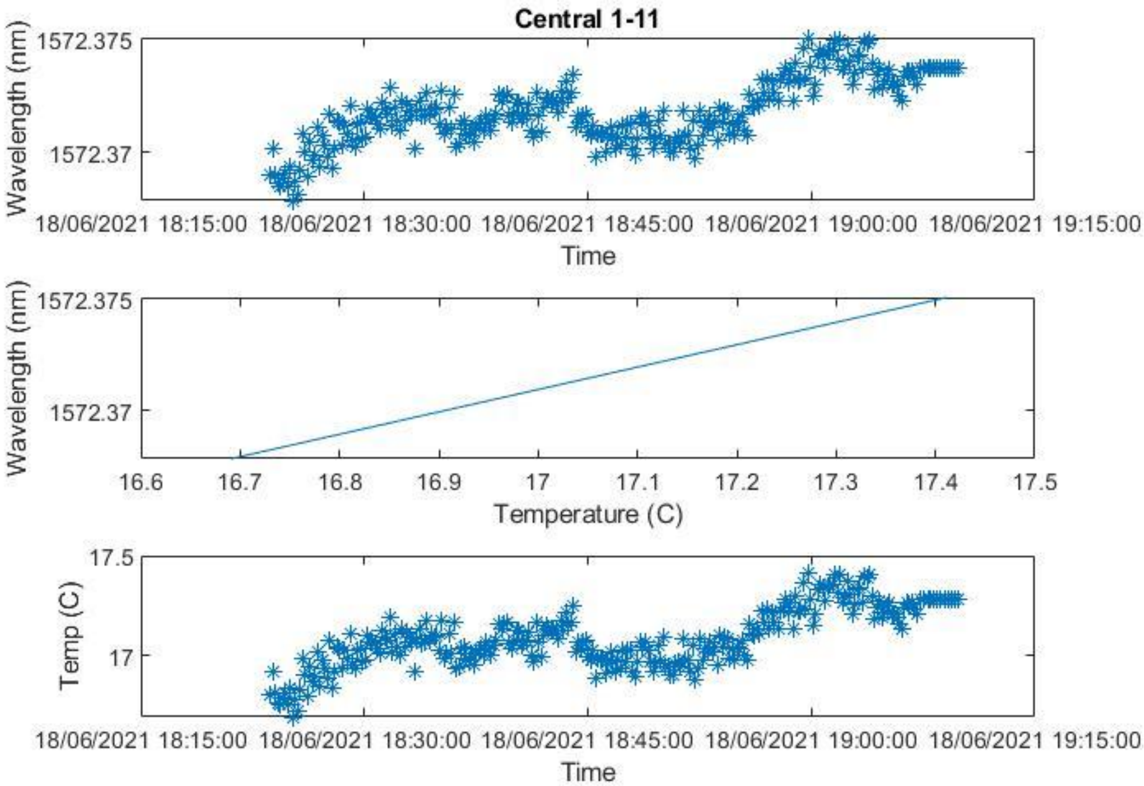

Central 1-6
Wavelength (nm)
1547.38
1547.375
1547.37
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time
Wavelength (nm)
1547.38
1547.375
1547.37
16.4
16.6
16.8
17
17.2
17.4
17.6
17.8
Temperature (C)
Temp (C)
18
17.5
17
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time

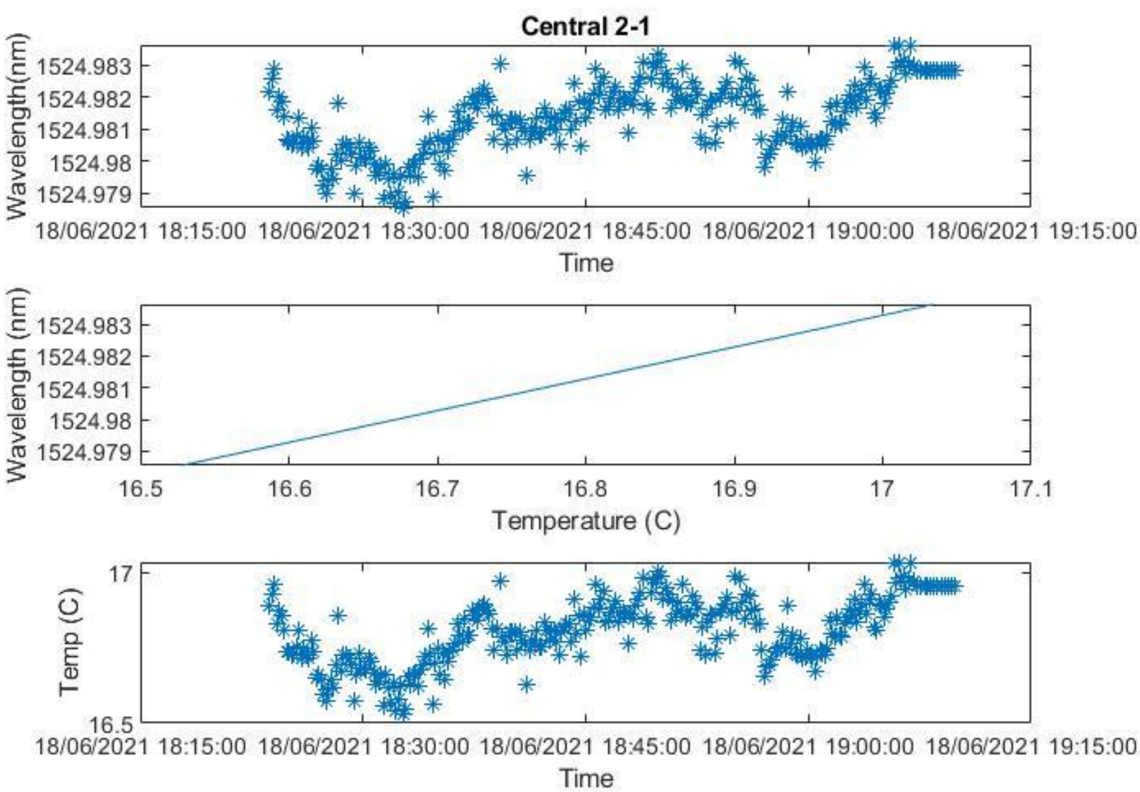

Central 1-7
Wavelength (nm)
1552.41
1552.405
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time
Wavelength (nm)
1552.41
1552.405
16.7
16.8
16.9
17
17.1
17.2
17.3
17.4
17.5
17.6
Temperature (C)
Temp (C)
17.5
17
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time

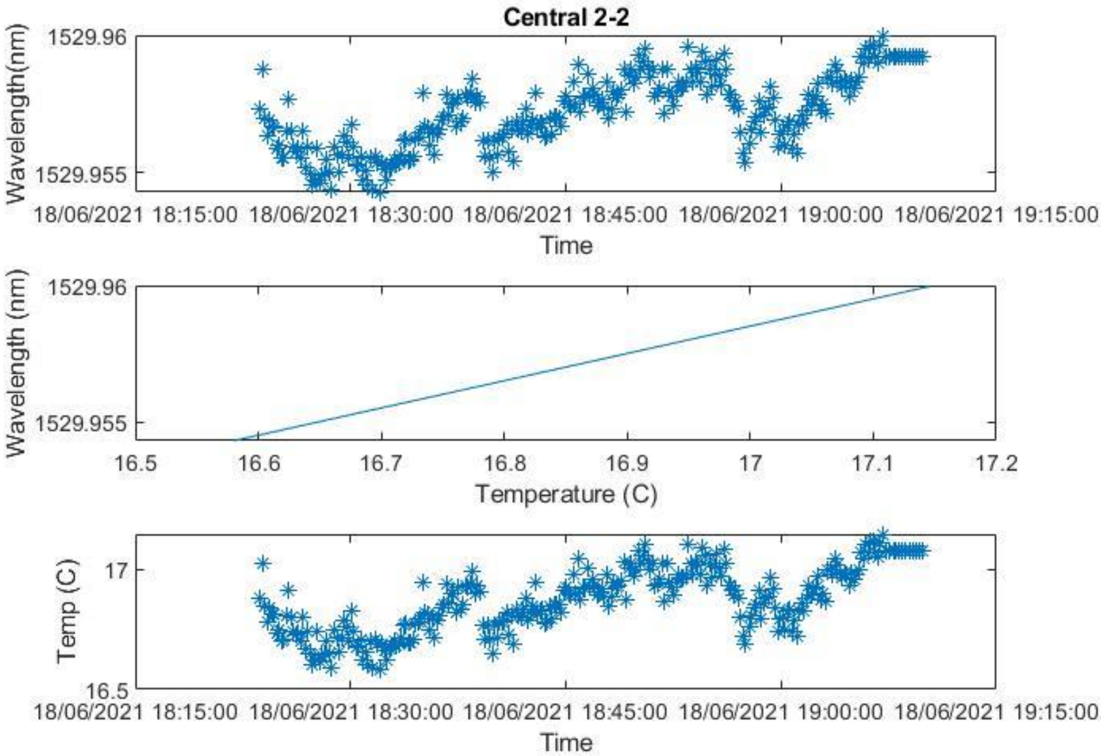

Central 1-8
Wavelength (nm)
1557.51
1557.505
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time
Wavelength (nm)
1557.51
1557.505
16.7
16.8
16.9
17
17.1
17.2
17.3
17.4
17.5
17.6
17.7
Temperature (C)
Temp (C)
17.5
17
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time

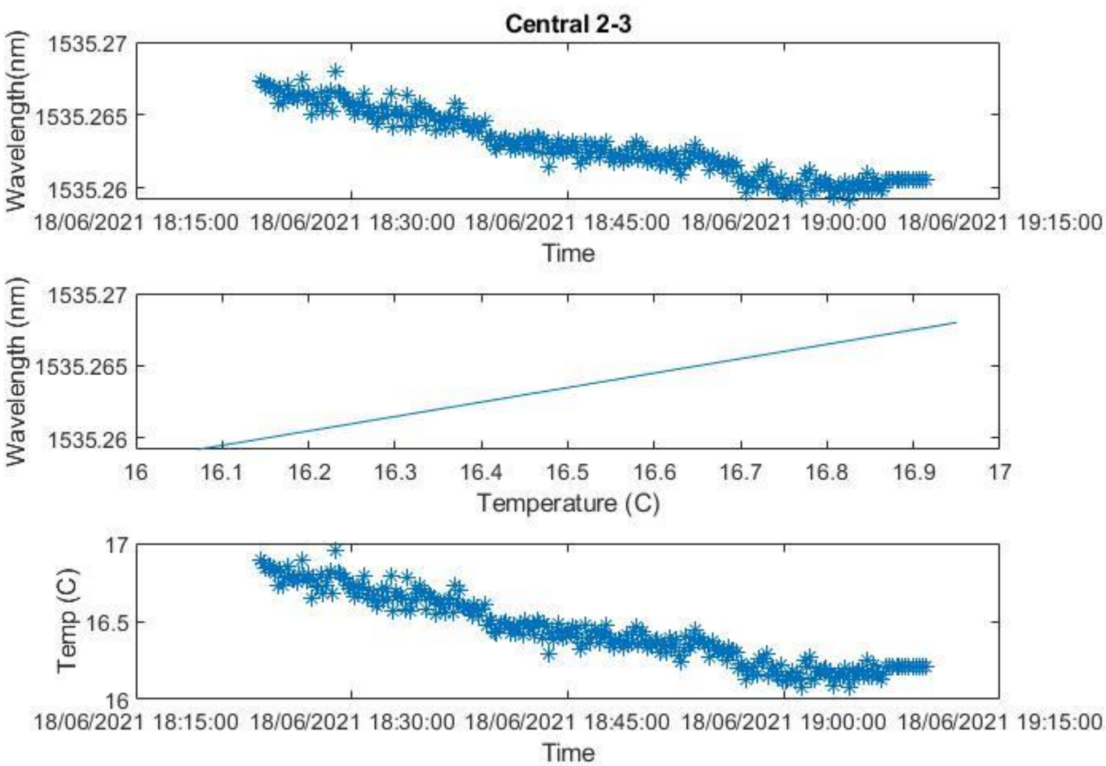

Central 1-9
Wavelength (nm)
Time
Temperature (C)
Temp (C)
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00

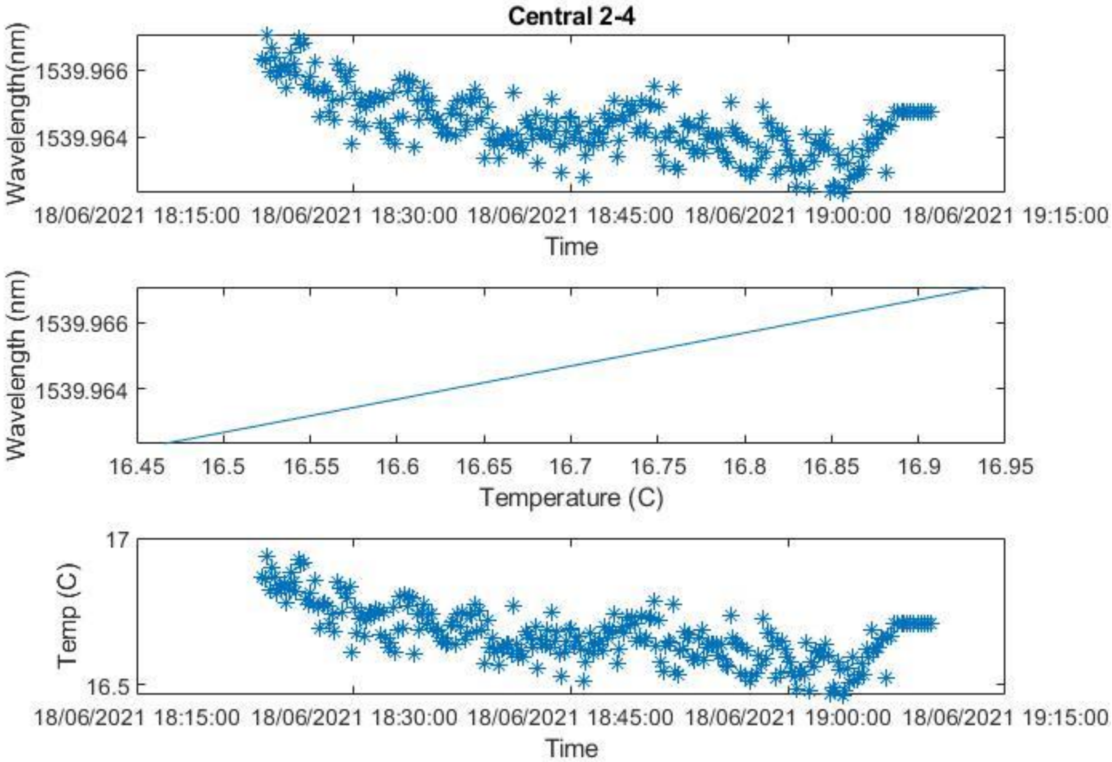

Central 1-10
Wavelength (nm)
Time
Temperature (C)
Temp (C)
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00

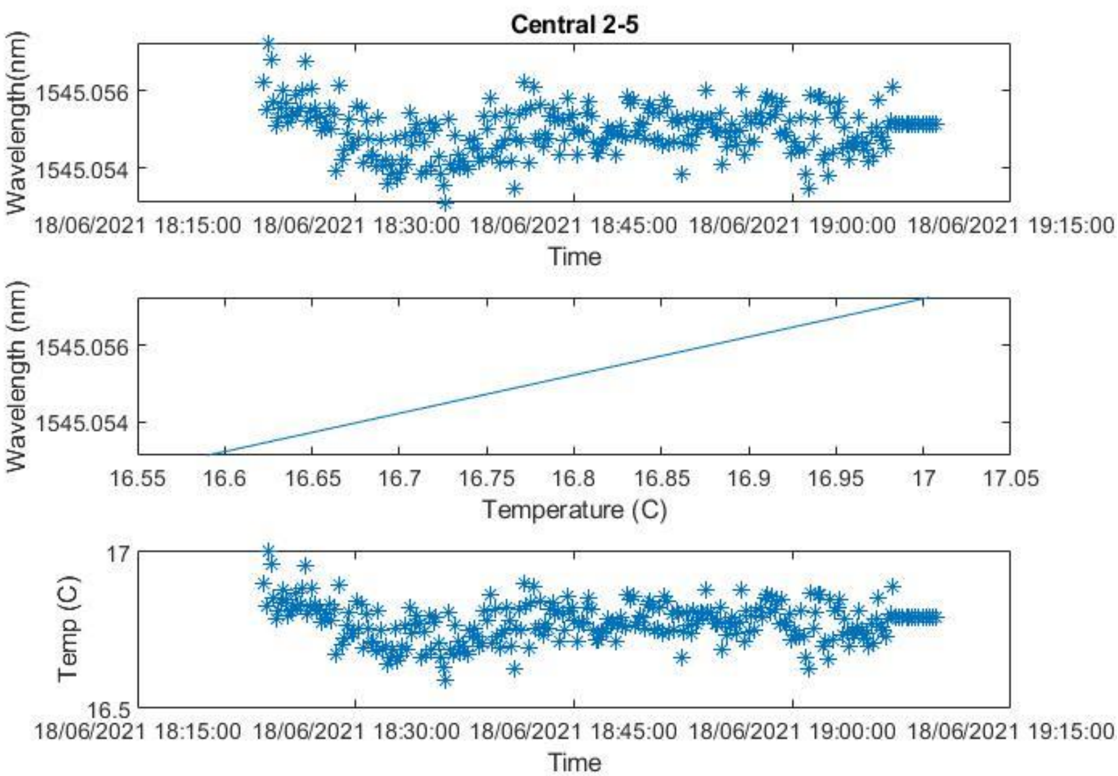

Central 1-11
Wavelength (nm)
1572.375
1572.37
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time
Wavelength (nm)
1572.375
1572.37
16.6
16.7
16.8
16.9
17
17.1
17.2
17.3
17.4
17.5
Temperature (C)
Temp (C)
17.5
17
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time

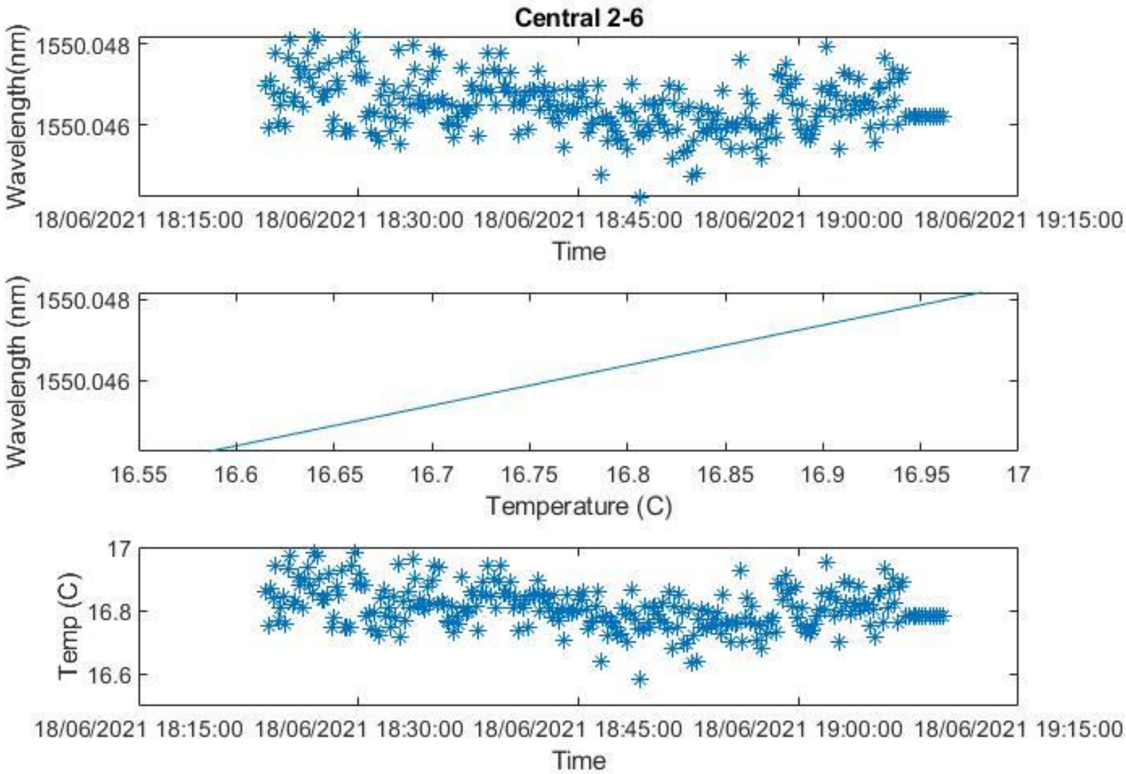

Central 2-1
Wavelength(nm)
1524.983
1524.982
1524.981
1524.98
1524.979
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time
Wavelength (nm)
1524.983
1524.982
1524.981
1524.98
1524.979
16.5
16.6
16.7
16.8
16.9
17
17.1
Temperature (C)
Temp (C)
17
16.5
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time

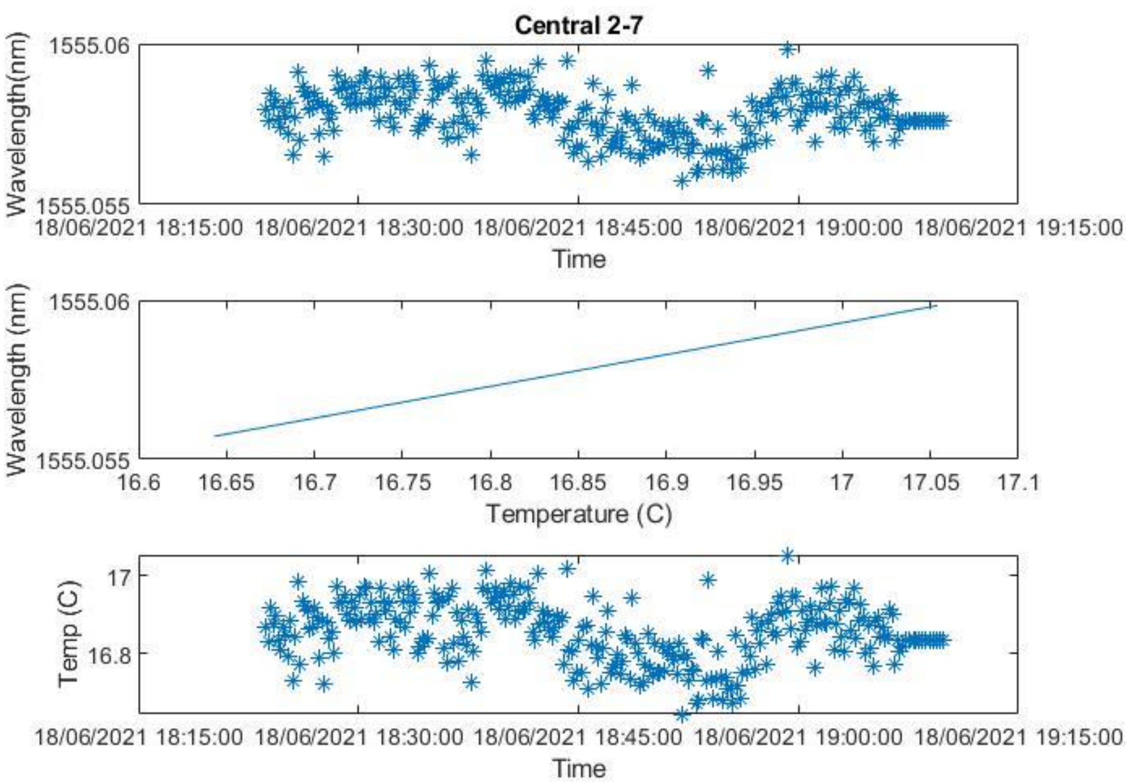

Central 2-2
Wavelength(nm)
1529.96
1529.955
18/06/2021 18:15:00 18/06/2021 18:30:00 18/06/2021 18:45:00 18/06/2021 19:00:00 18/06/2021 19:15:00
Time
Wavelength (nm)
1529.96
1529.955
16.5 16.6 16.7 16.8 16.9 17 17.1 17.2
Temperature (C)
Temp (C)
17
16.5
18/06/2021 18:15:00 18/06/2021 18:30:00 18/06/2021 18:45:00 18/06/2021 19:00:00 18/06/2021 19:15:00
Time

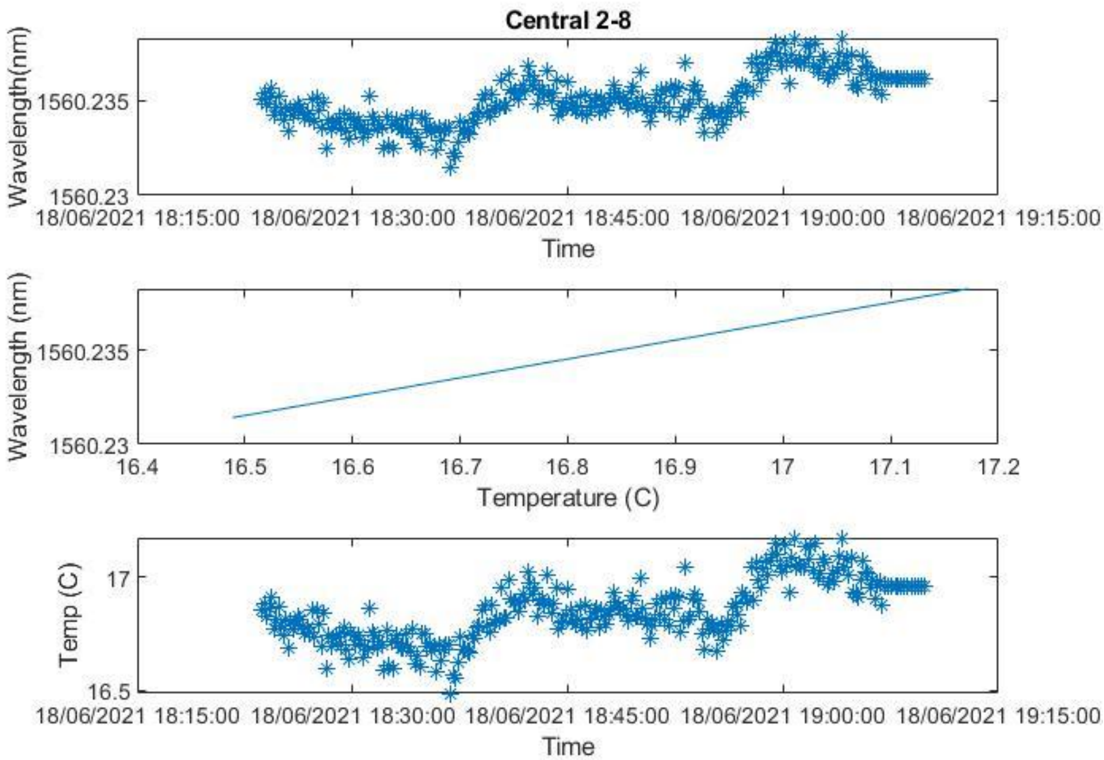

Central 2-3
Wavelength(nm)
1535.27
1535.265
1535.26
18/06/2021 18:15:00 18/06/2021 18:30:00 18/06/2021 18:45:00 18/06/2021 19:00:00 18/06/2021 19:15:00
Time
Wavelength (nm)
1535.27
1535.265
1535.26
16 16.1 16.2 16.3 16.4 16.5 16.6 16.7 16.8 16.9 17
Temperature (C)
Temp (C)
17
16.5
16
18/06/2021 18:15:00 18/06/2021 18:30:00 18/06/2021 18:45:00 18/06/2021 19:00:00 18/06/2021 19:15:00
Time

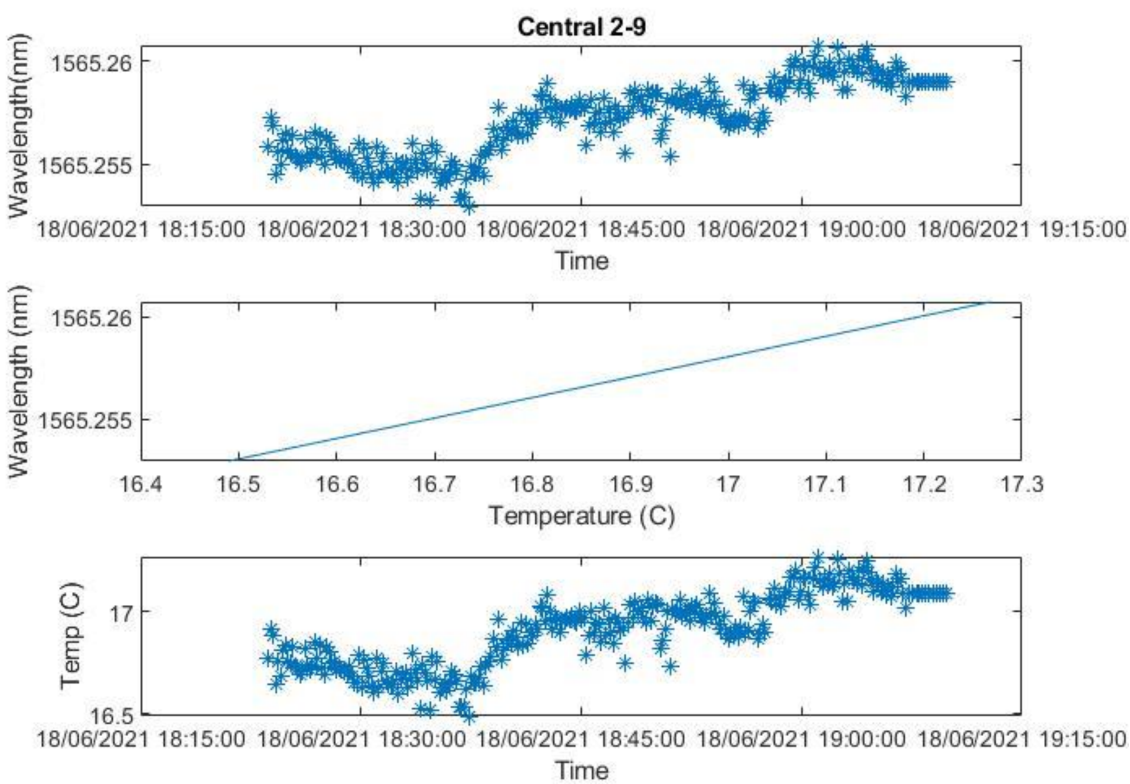

Central 2-4
Wavelength(nm)
1539.966
1539.964
18/06/2021 18:15:00 18/06/2021 18:30:00 18/06/2021 18:45:00 18/06/2021 19:00:00 18/06/2021 19:15:00
Time
Wavelength (nm)
16.45 16.5 16.55 16.6 16.65 16.7 16.75 16.8 16.85 16.9 16.95
Temperature (C)
Temp (C)
17
16.5

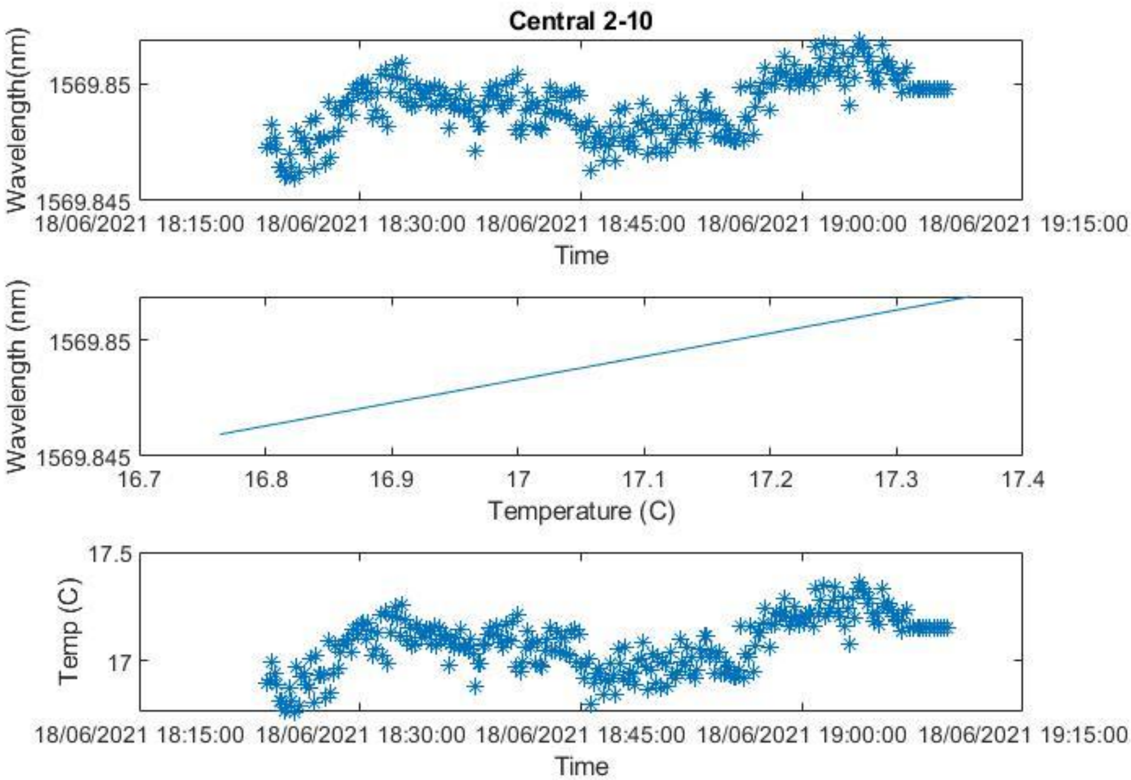

Central 2-5
Wavelength(nm)
1545.056
1545.054
18/06/2021 18:15:00 18/06/2021 18:30:00 18/06/2021 18:45:00 18/06/2021 19:00:00 18/06/2021 19:15:00
Time
Wavelength (nm)
16.55 16.6 16.65 16.7 16.75 16.8 16.85 16.9 16.95 17 17.05
Temperature (C)
Temp (C)
17
16.5

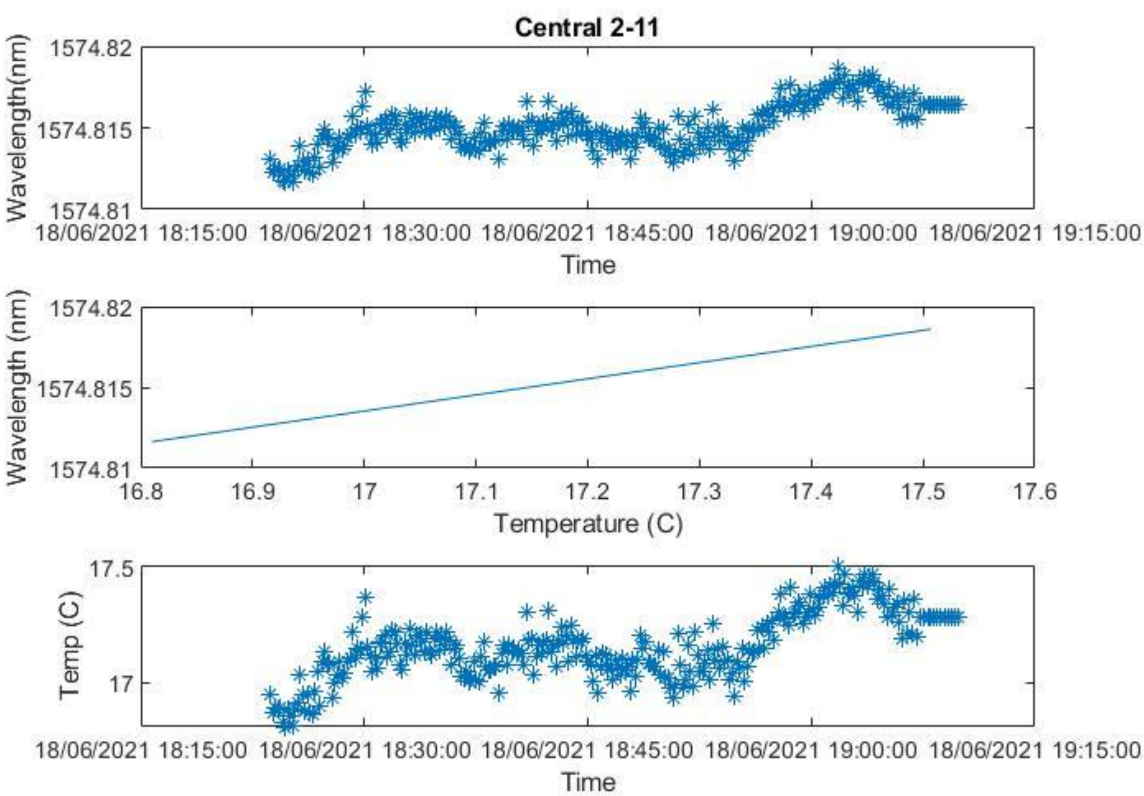

Central 2-6
Wavelength(nm)
1550.048
1550.046
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time
Wavelength (nm)
1550.048
1550.046
16.55
16.6
16.65
16.7
16.75
16.8
16.85
16.9
16.95
17
Temperature (C)
Temp (C)
17
16.8
16.6
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time


Central 2-7
Wavelength(nm)
1555.06
1555.055
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time
Wavelength (nm)
1555.06
1555.055
16.6
16.65
16.7
16.75
16.8
16.85
16.9
16.95
17
17.05
17.1
Temperature (C)
Temp (C)
17
16.8
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time


Central 2-8
Wavelength(nm)
1560.235
1560.23
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time
Wavelength (nm)
1560.235
1560.23
16.4
16.5
16.6
16.7
16.8
16.9
17
17.1
17.2
Temperature (C)
Temp (C)
17
16.5
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time

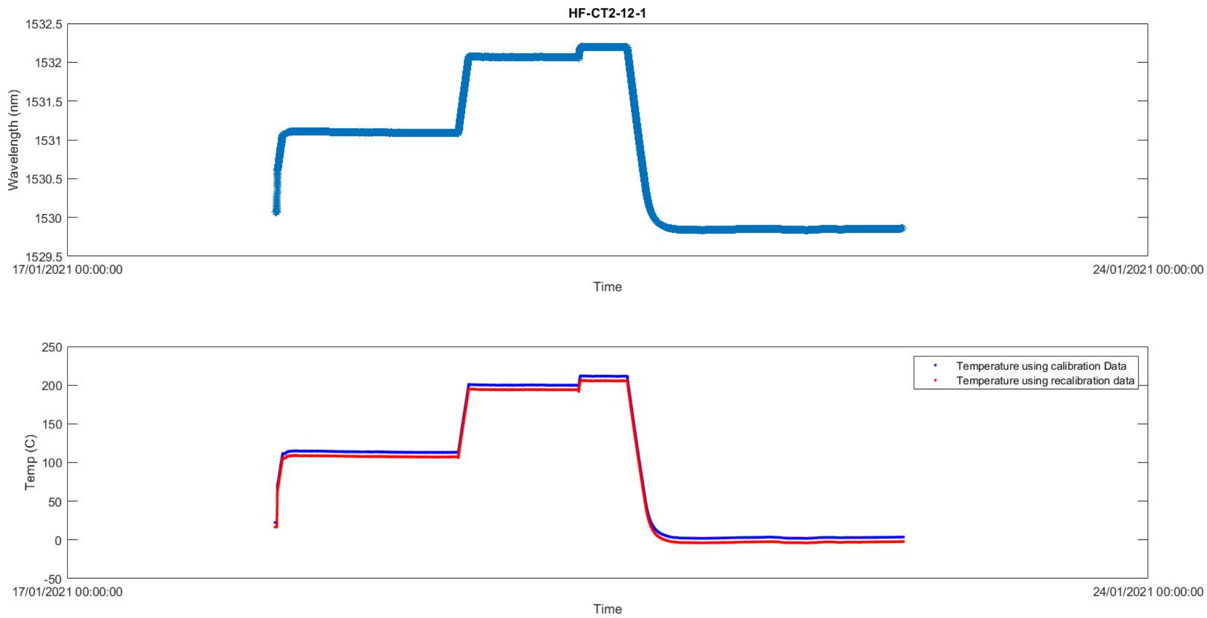

Central 2-9
Wavelength(nm)
1565.26
1565.255
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time
Wavelength (nm)
1565.26
1565.255
16.4
16.5
16.6
16.7
16.8
16.9
17
17.1
17.2
17.3
Temperature (C)
Temp (C)
17
16.5
18/06/2021 18:15:00
18/06/2021 18:30:00
18/06/2021 18:45:00
18/06/2021 19:00:00
18/06/2021 19:15:00
Time

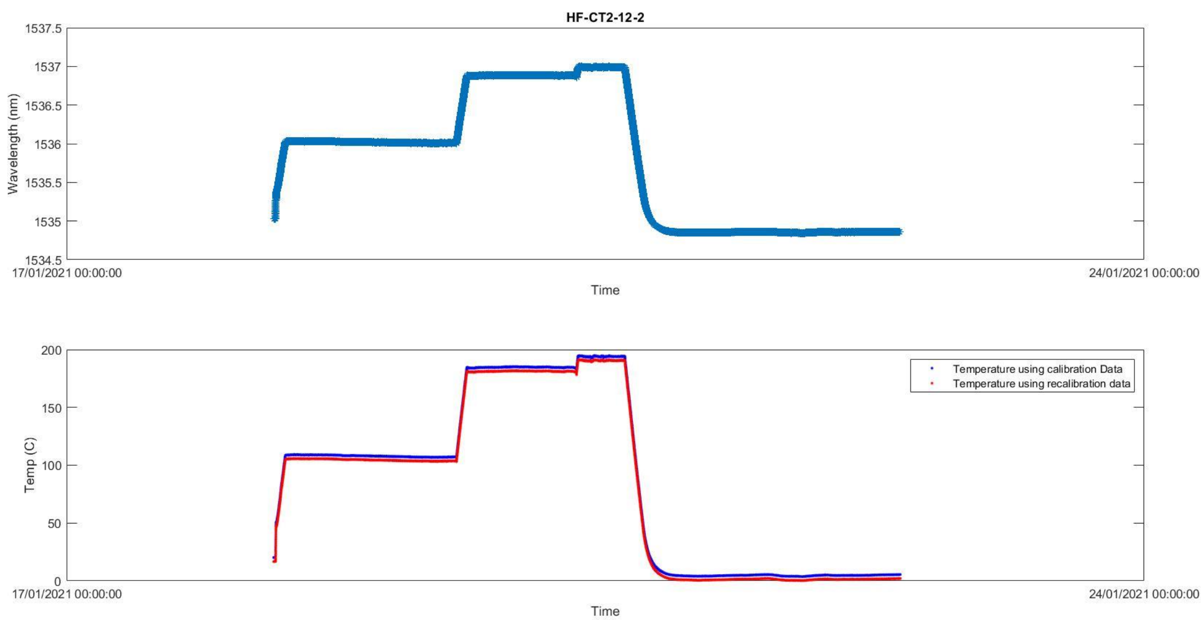

Central 2-10
Wavelength(nm)
1569.85
1569.845
18/06/2021 18:15:00 18/06/2021 18:30:00 18/06/2021 18:45:00 18/06/2021 19:00:00 18/06/2021 19:15:00
Time
Wavelength (nm)
1569.85
1569.845
16.7 16.8 16.9 17 17.1 17.2 17.3 17.4
Temperature (C)
Temp (C)
17.5
17
18/06/2021 18:15:00 18/06/2021 18:30:00 18/06/2021 18:45:00 18/06/2021 19:00:00 18/06/2021 19:15:00
Time

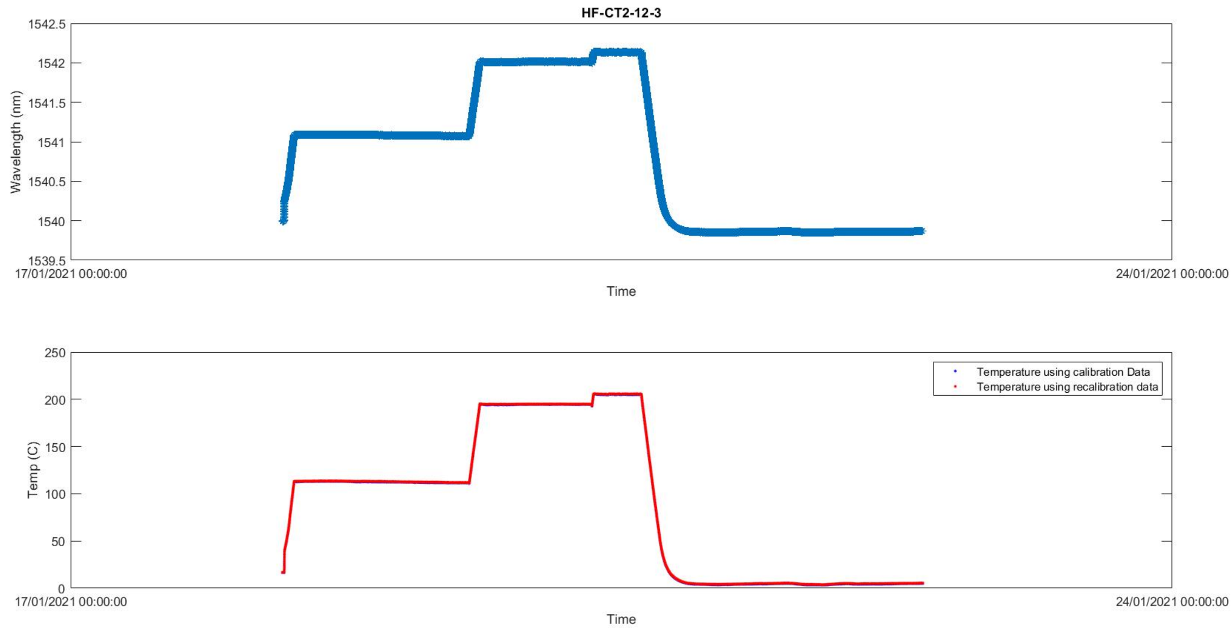

Central 2-11
Wavelength(nm)
1574.82
1574.815
1574.81
18/06/2021 18:15:00 18/06/2021 18:30:00 18/06/2021 18:45:00 18/06/2021 19:00:00 18/06/2021 19:15:00
Time
Wavelength (nm)
1574.82
1574.815
1574.81
16.8 16.9 17 17.1 17.2 17.3 17.4 17.5 17.6
Temperature (C)
Temp (C)
17.5
17
18/06/2021 18:15:00 18/06/2021 18:30:00 18/06/2021 18:45:00 18/06/2021 19:00:00 18/06/2021 19:15:00
Time

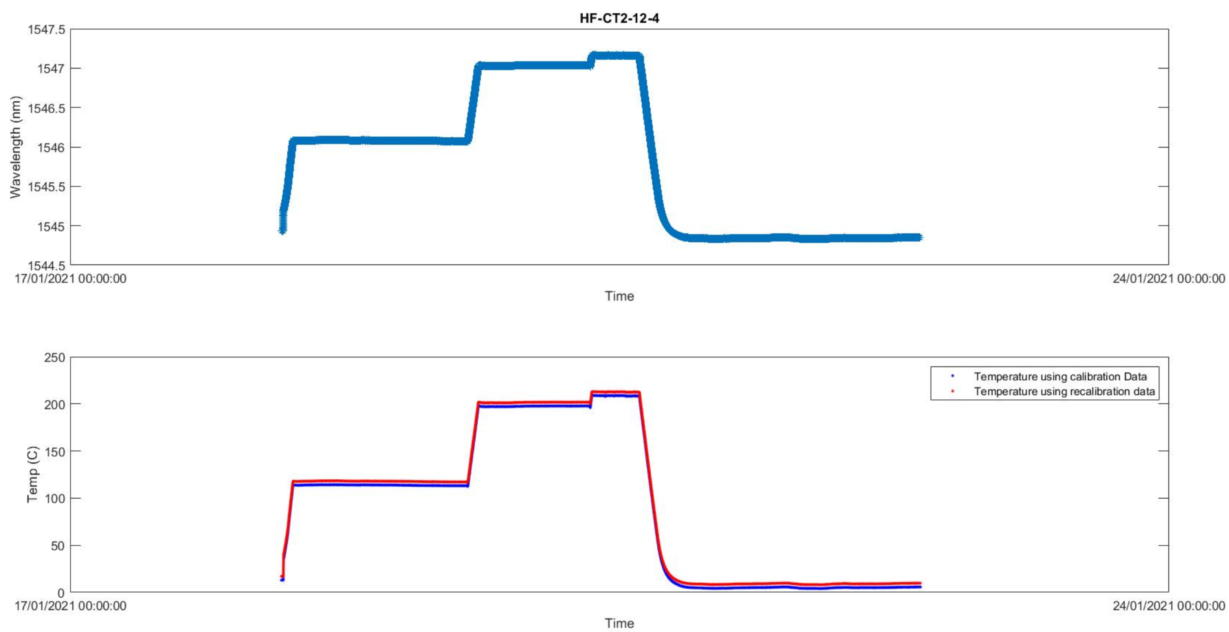
9.3 Bakeout Plots

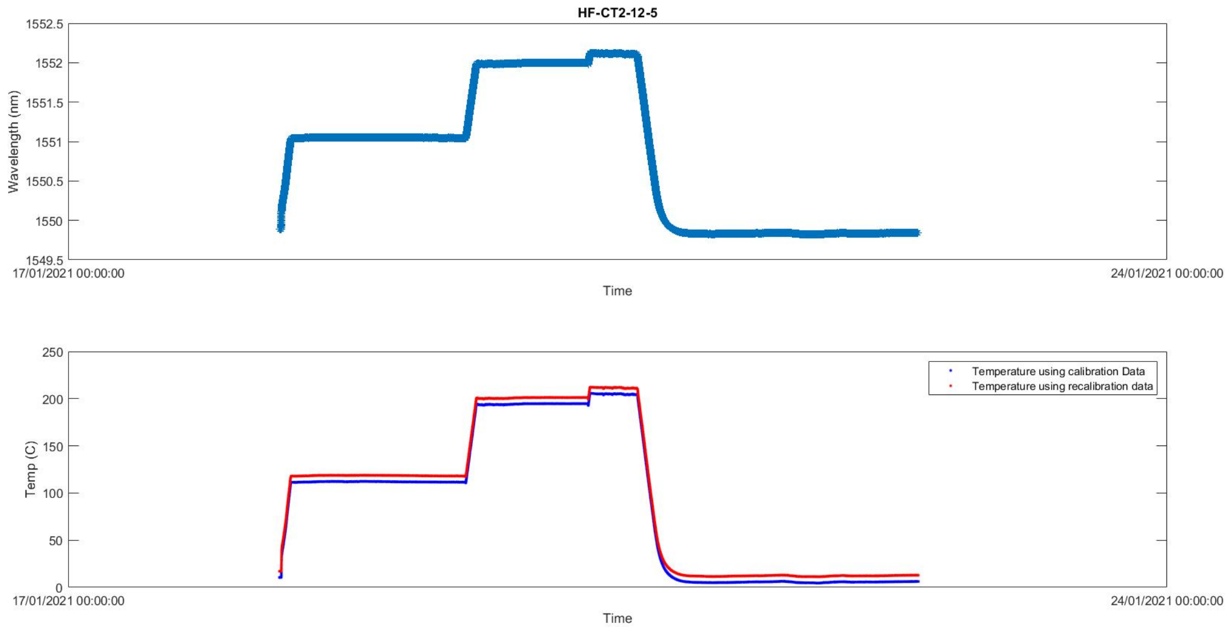
9.3.1 HF_CT2 #2 Plots

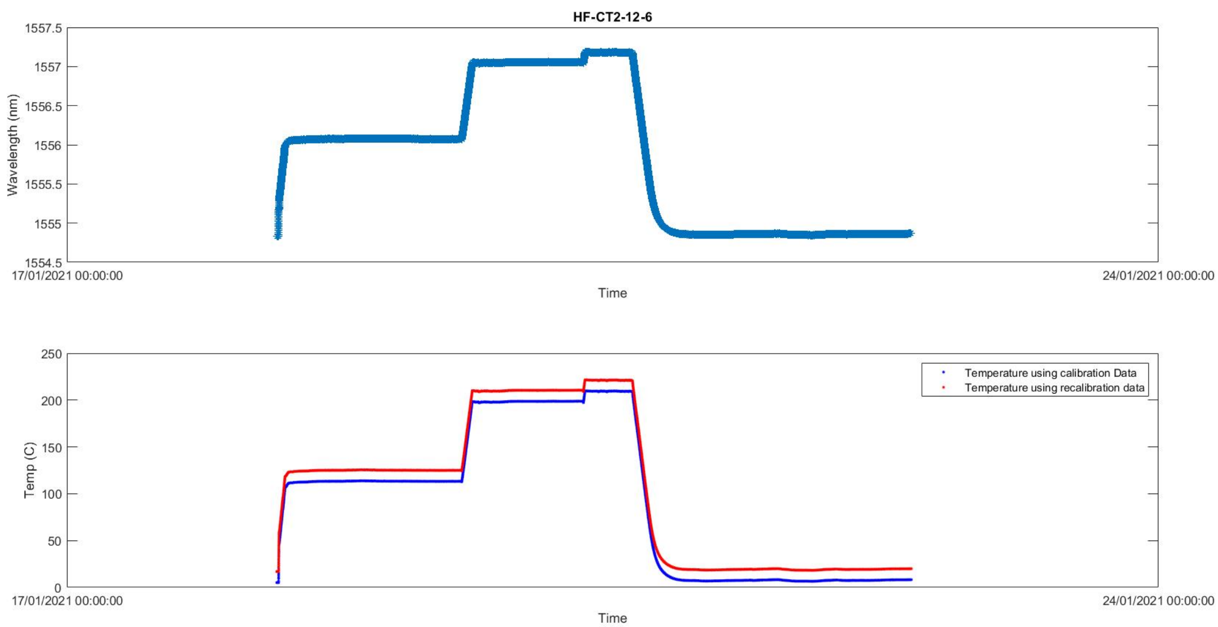


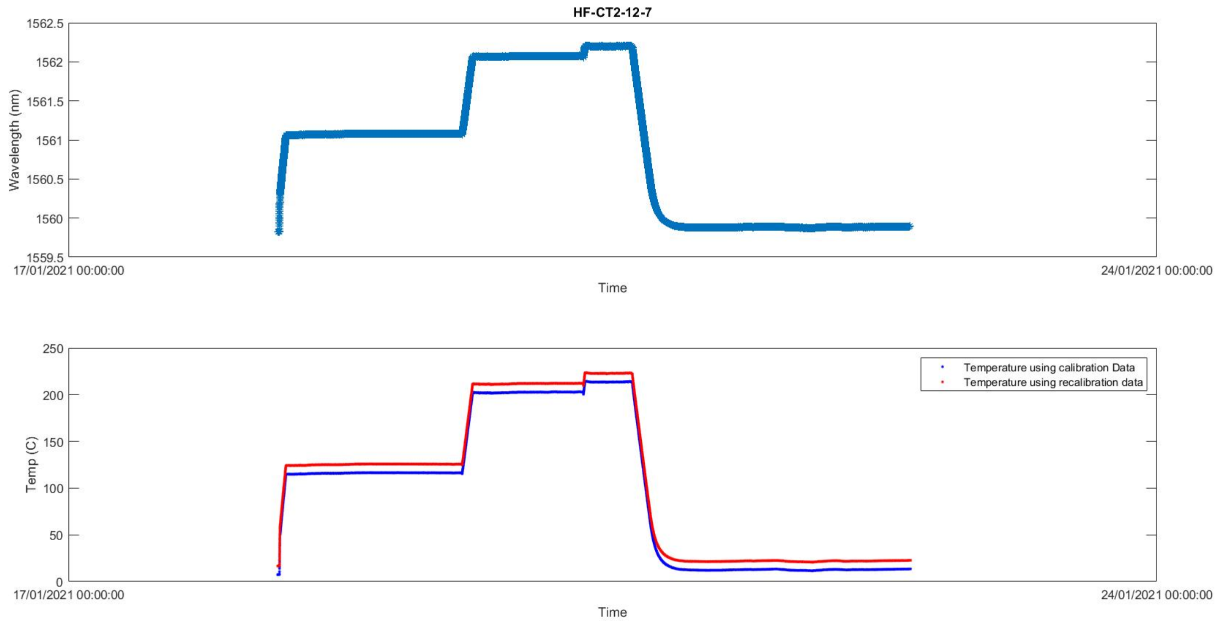


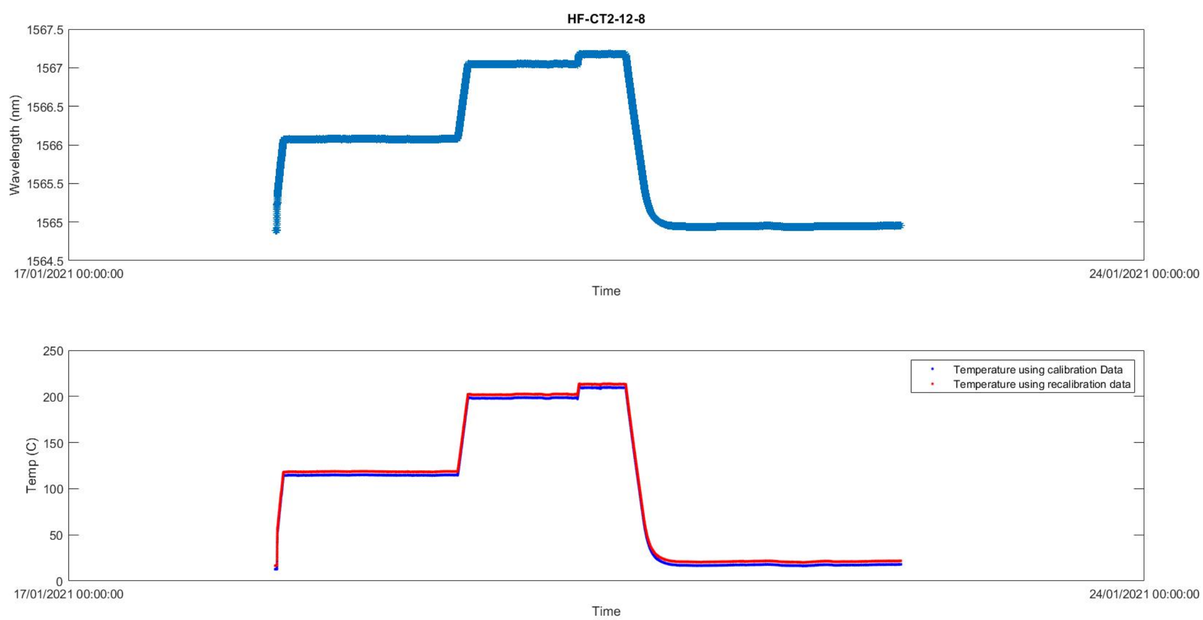

HF-CT2-12-3
Wavelength (nm)
Time
17/01/2021 00:00:00
24/01/2021 00:00:00
Temp (C)
Temperature using calibration Data
Temperature using recalibration data

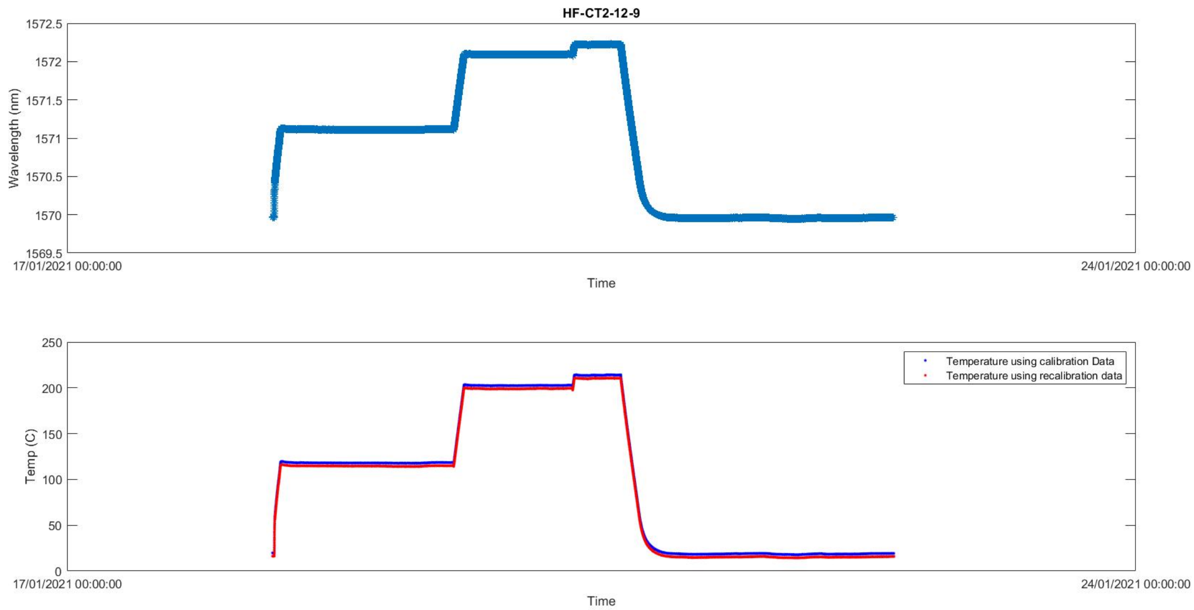

HF-CT2-12-4
Wavelength (nm)
Time
17/01/2021 00:00:00
24/01/2021 00:00:00
Temp (C)
Temperature using calibration Data
Temperature using recalibration data

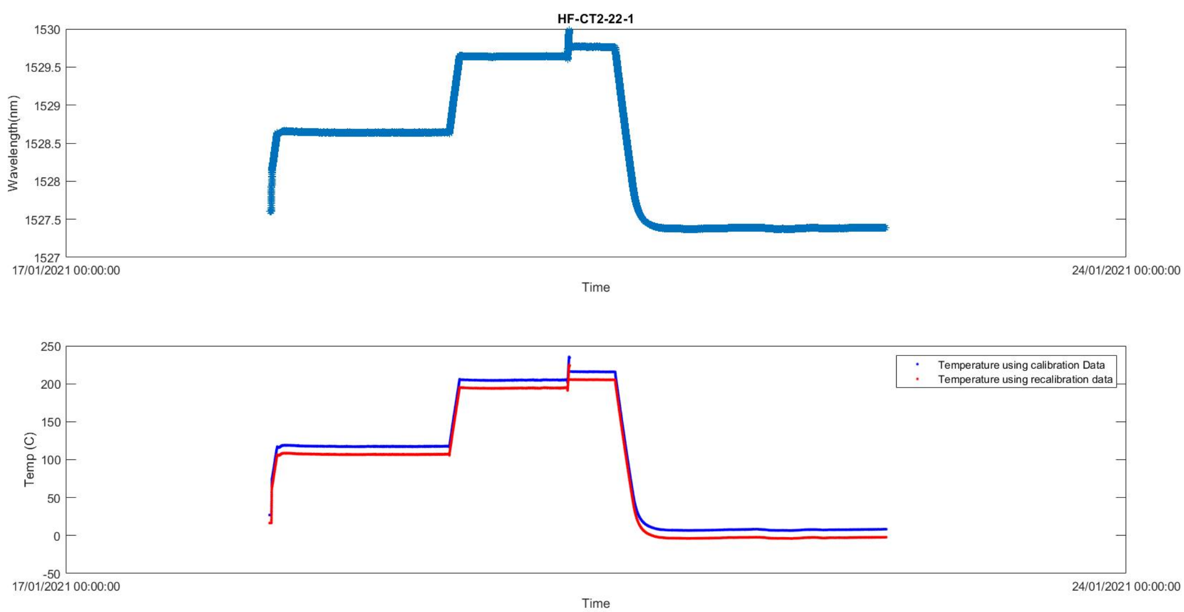

HF-CT2-12-5
Wavelength (nm)
1552.5
1552
1551.5
1551
1550.5
1550
1549.5
17/01/2021 00:00:00
24/01/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data
17/01/2021 00:00:00
24/01/2021 00:00:00
Time

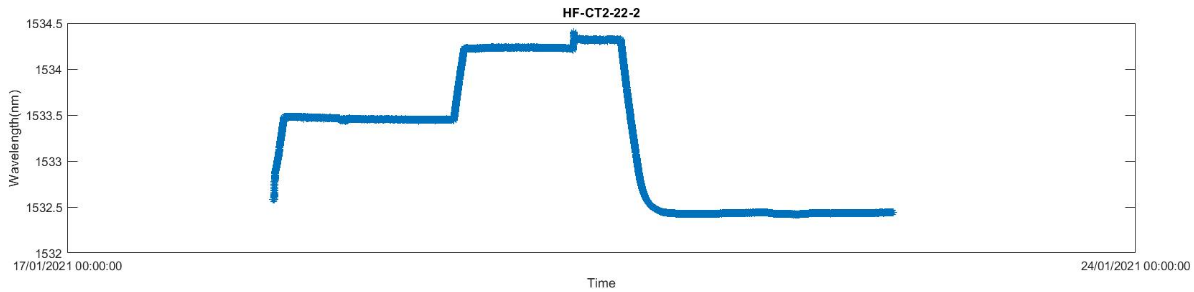

HF-CT2-12-6
Wavelength (nm)
1557.5
1557
1556.5
1556
1555.5
1555
1554.5
17/01/2021 00:00:00
24/01/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data
17/01/2021 00:00:00
24/01/2021 00:00:00
Time

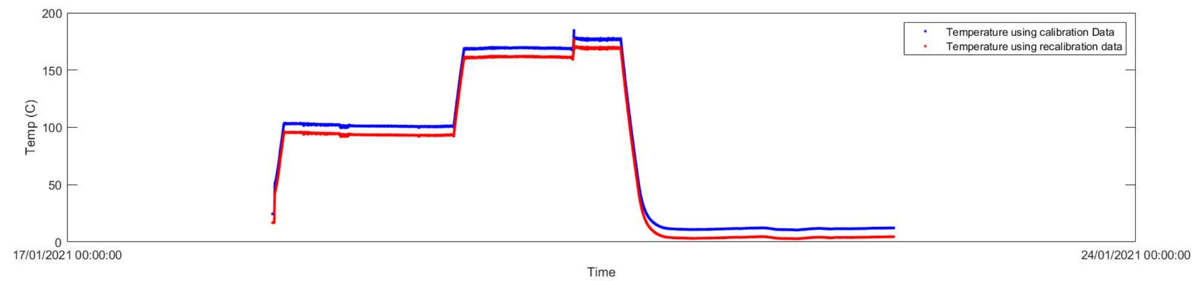

HF-CT2-12-7
Wavelength (nm)
1562.5
1562
1561.5
1561
1560.5
1560
1559.5
17/01/2021 00:00:00
24/01/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data
17/01/2021 00:00:00
24/01/2021 00:00:00
Time

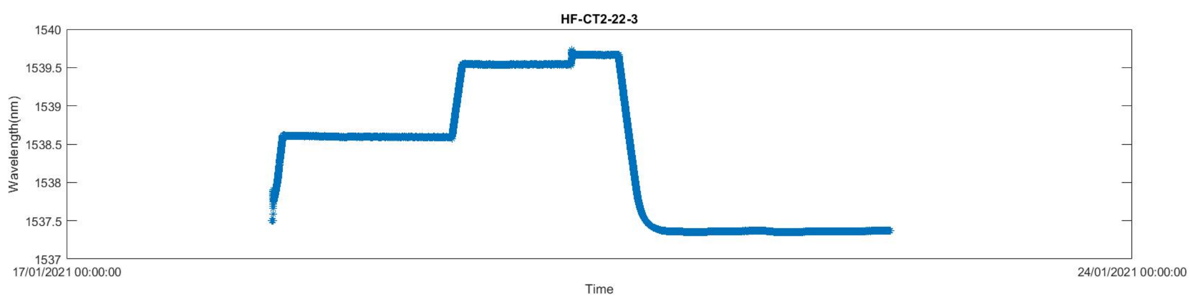

HF-CT2-12-8
Wavelength (nm)
1567.5
1567
1566.5
1566
1565.5
1565
1564.5
17/01/2021 00:00:00
24/01/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data
17/01/2021 00:00:00
24/01/2021 00:00:00
Time

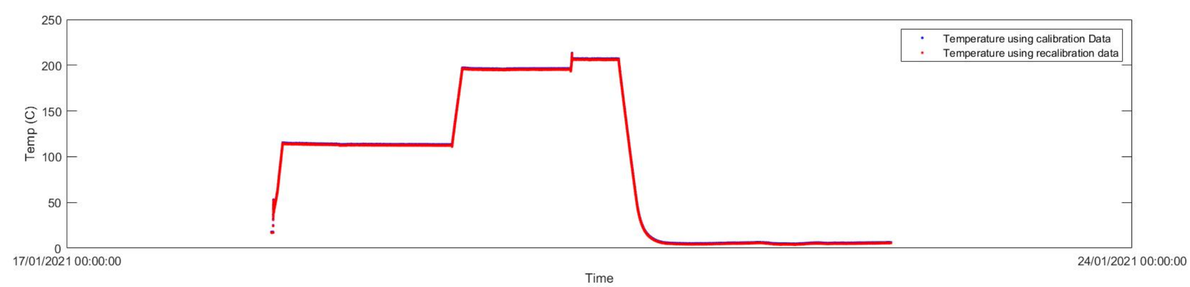

HF-CT2-12-9
Wavelength (nm)
1572.5
1572
1571.5
1571
1570.5
1570
1569.5
17/01/2021 00:00:00
24/01/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data
17/01/2021 00:00:00
24/01/2021 00:00:00
Time

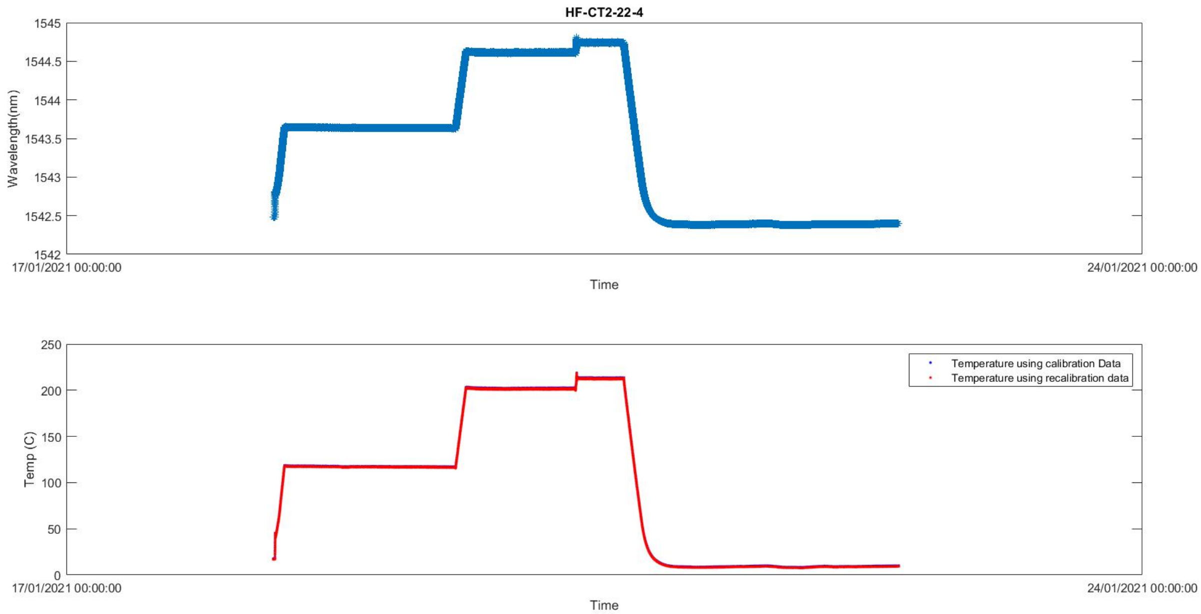

HF-CT2-22-1
Wavelength(nm)
1530
1529.5
1529
1528.5
1528
1527.5
1527
17/01/2021 00:00:00
24/01/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
-50
Temperature using calibration Data
Temperature using recalibration data
17/01/2021 00:00:00
24/01/2021 00:00:00
Time

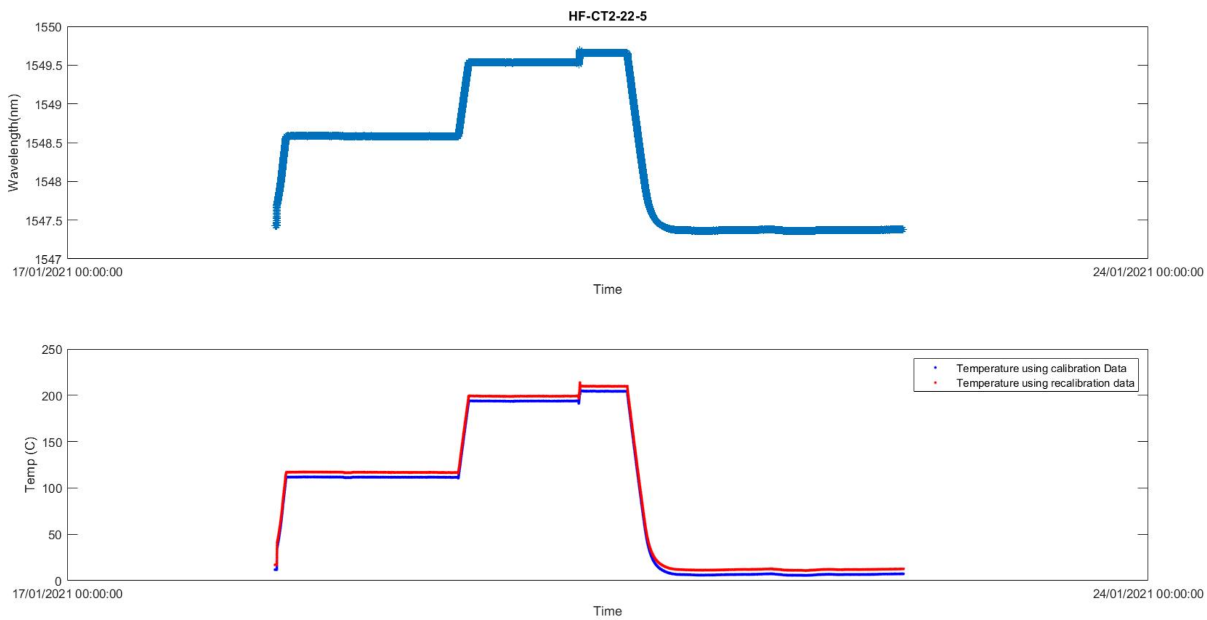

HF-CT2-22-2
Wavelength(nm)
1534.5
1534
1533.5
1533
1532.5
1532
17/01/2021 00:00:00
24/01/2021 00:00:00
Time

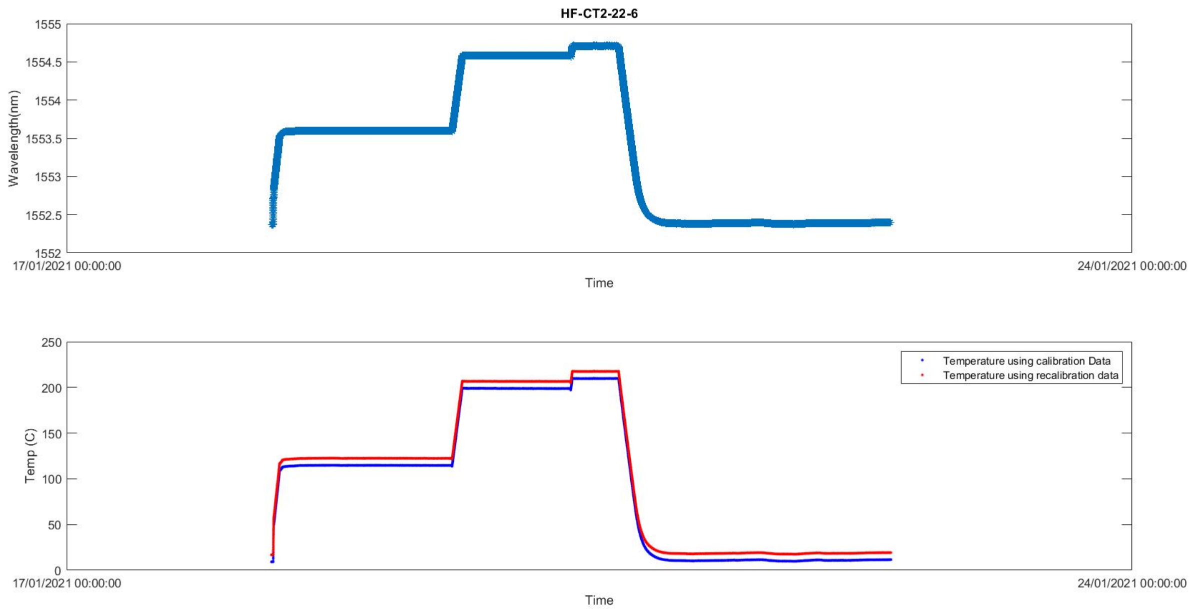

Temp (C)
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data
17/01/2021 00:00:00
24/01/2021 00:00:00
Time

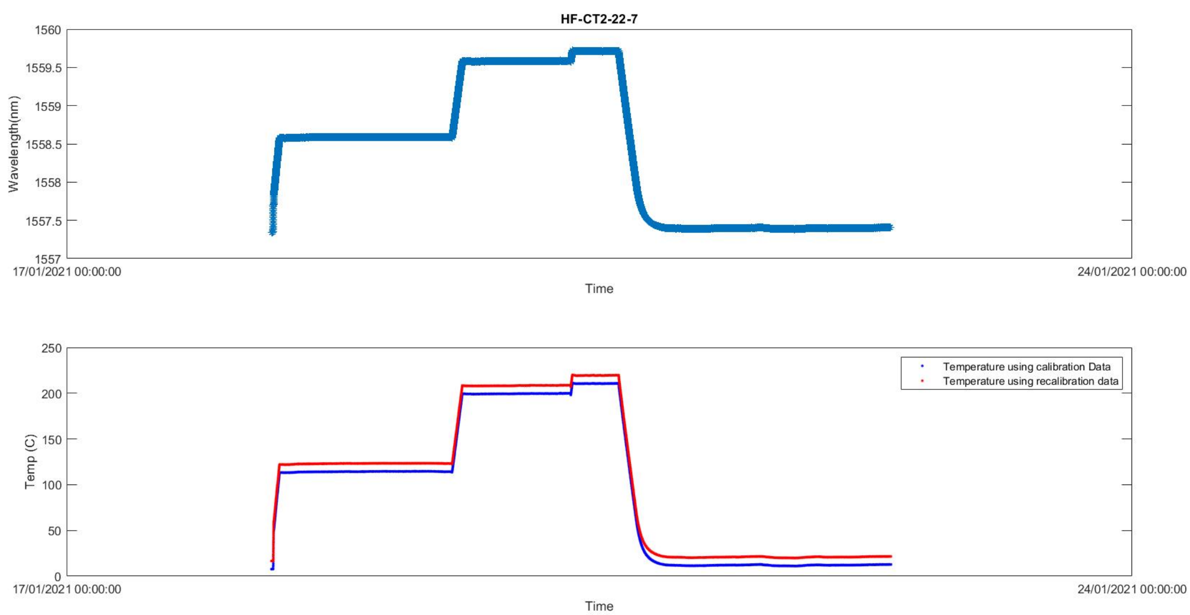

HF-CT2-22-3
Wavelength(nm)
1540
1539.5
1539
1538.5
1538
1537.5
1537
17/01/2021 00:00:00
24/01/2021 00:00:00
Time

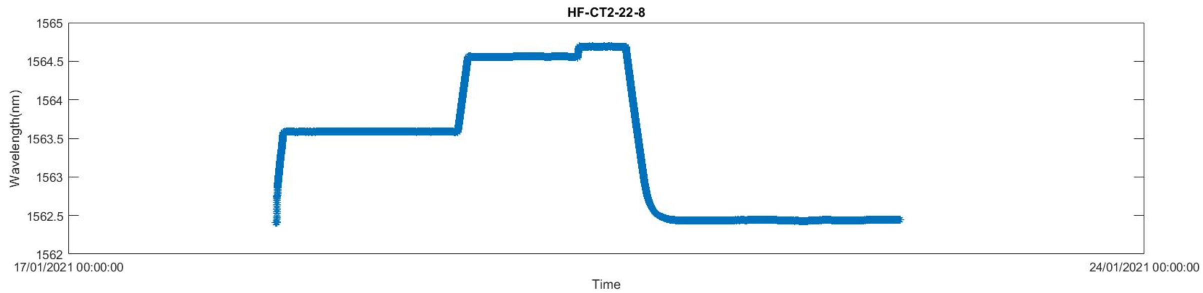

Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data
17/01/2021 00:00:00
24/01/2021 00:00:00
Time

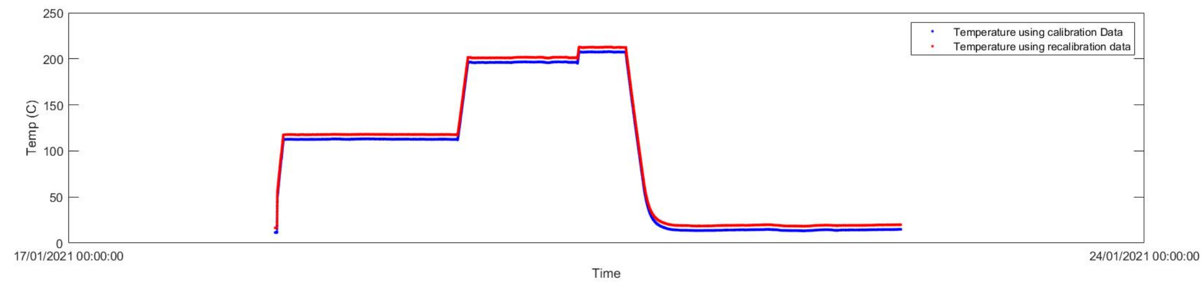

HF-CT2-22-4
Wavelength(nm)
1545
1544.5
1544
1543.5
1543
1542.5
1542
17/01/2021 00:00:00
24/01/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data
17/01/2021 00:00:00
24/01/2021 00:00:00
Time

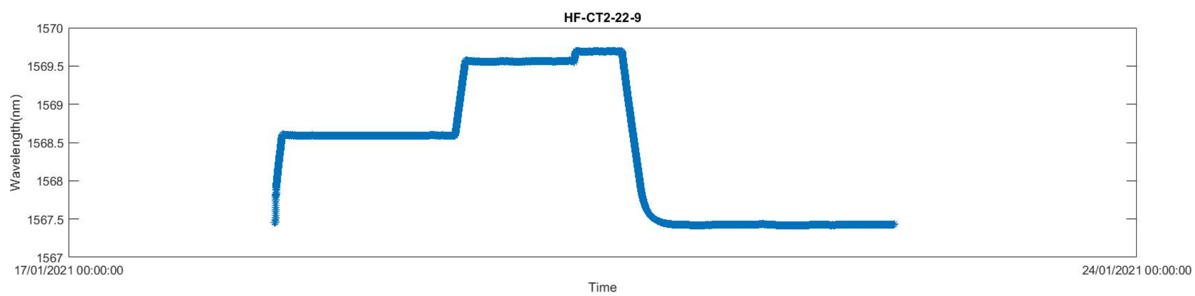

HF-CT2-22-5
Wavelength(nm)
1550
1549.5
1549
1548.5
1548
1547.5
1547
17/01/2021 00:00:00
24/01/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data
17/01/2021 00:00:00
24/01/2021 00:00:00
Time

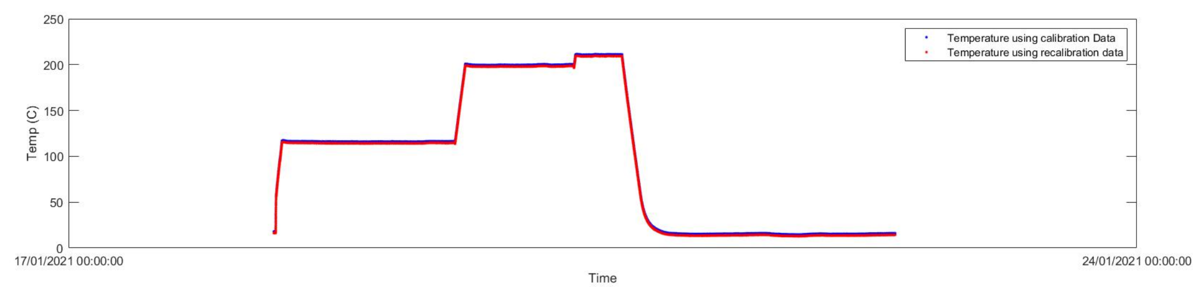

HF-CT2-22-6
Wavelength(nm)
1555
1554.5
1554
1553.5
1553
1552.5
1552
17/01/2021 00:00:00
24/01/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data
17/01/2021 00:00:00
24/01/2021 00:00:00
Time


HF-CT2-22-7
Wavelength(nm)
1560
1559.5
1559
1558.5
1558
1557.5
1557
17/01/2021 00:00:00
24/01/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data
17/01/2021 00:00:00
24/01/2021 00:00:00
Time

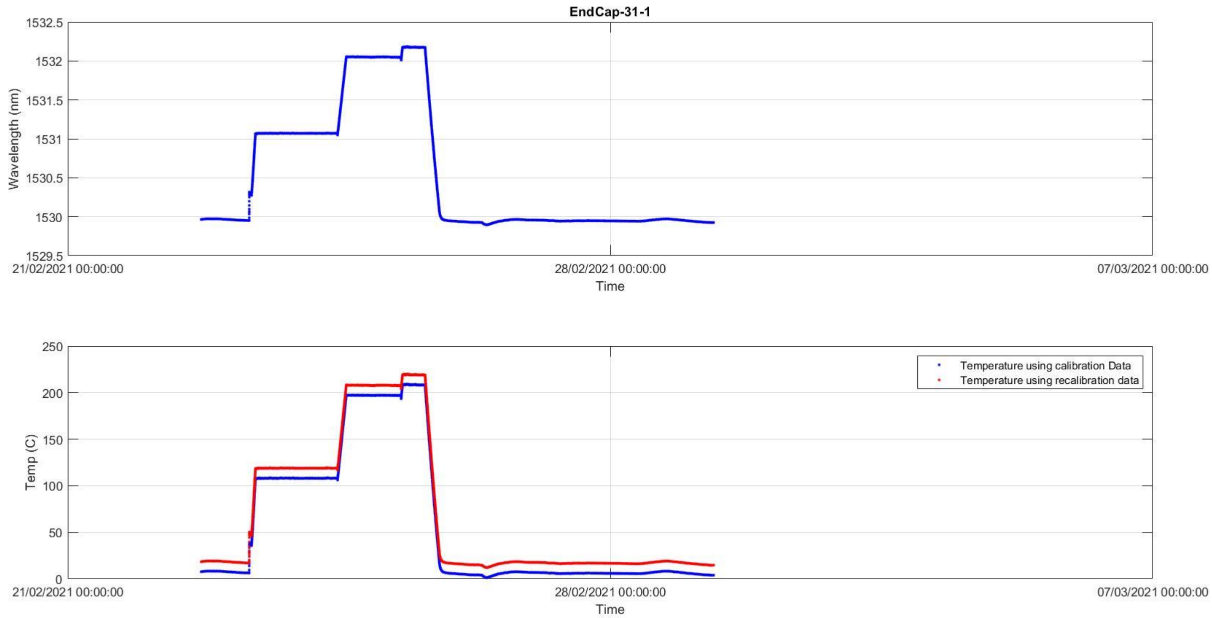

HF-CT2-22-8
Wavelength(nm)
1565
1564.5
1564
1563.5
1563
1562.5
1562
17/01/2021 00:00:00
24/01/2021 00:00:00
Time

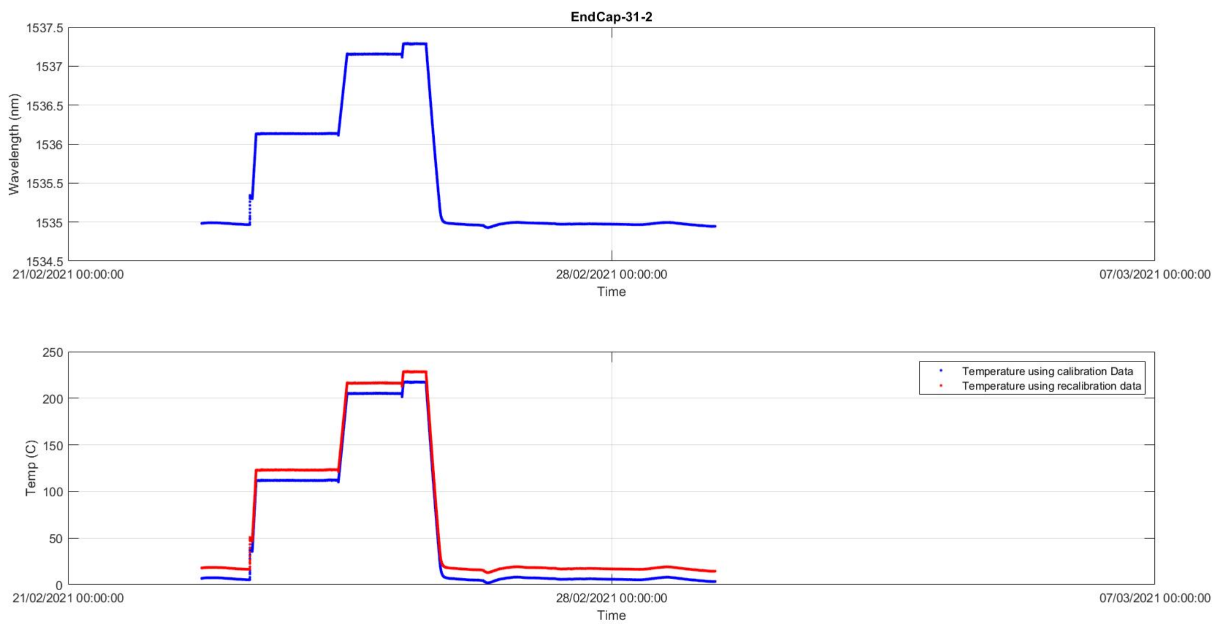

Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data
17/01/2021 00:00:00
24/01/2021 00:00:00
Time

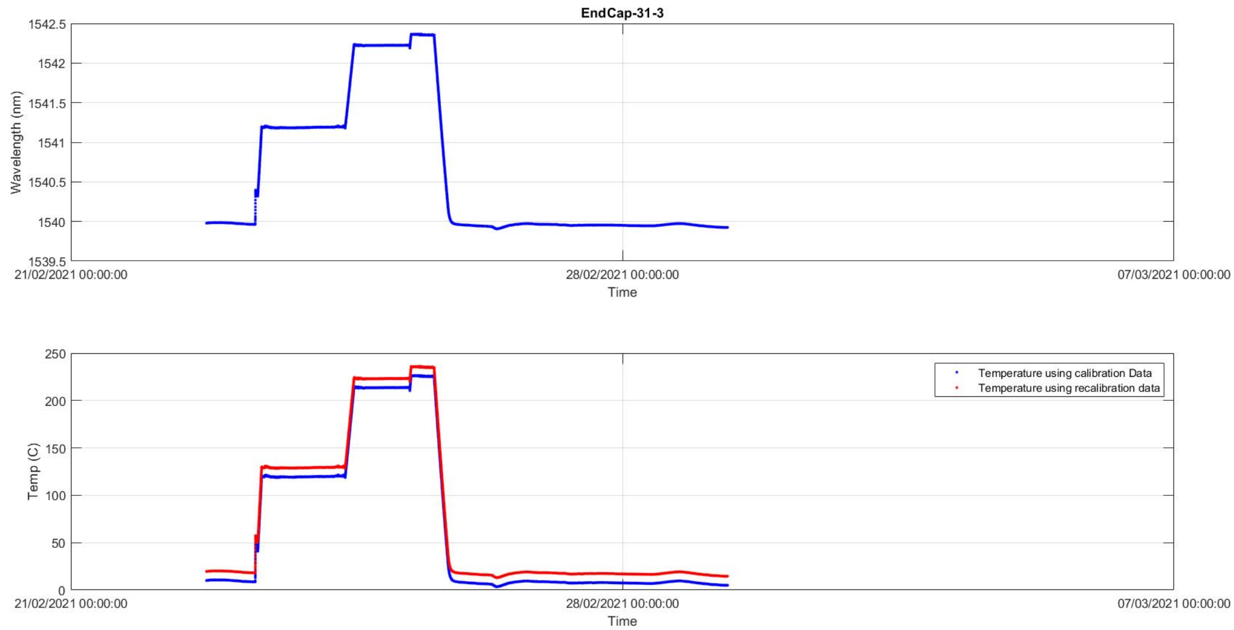

HF-CT2-22-9
Wavelength(nm)
1570
1569.5
1569
1568.5
1568
1567.5
1567
17/01/2021 00:00:00
24/01/2021 00:00:00
Time

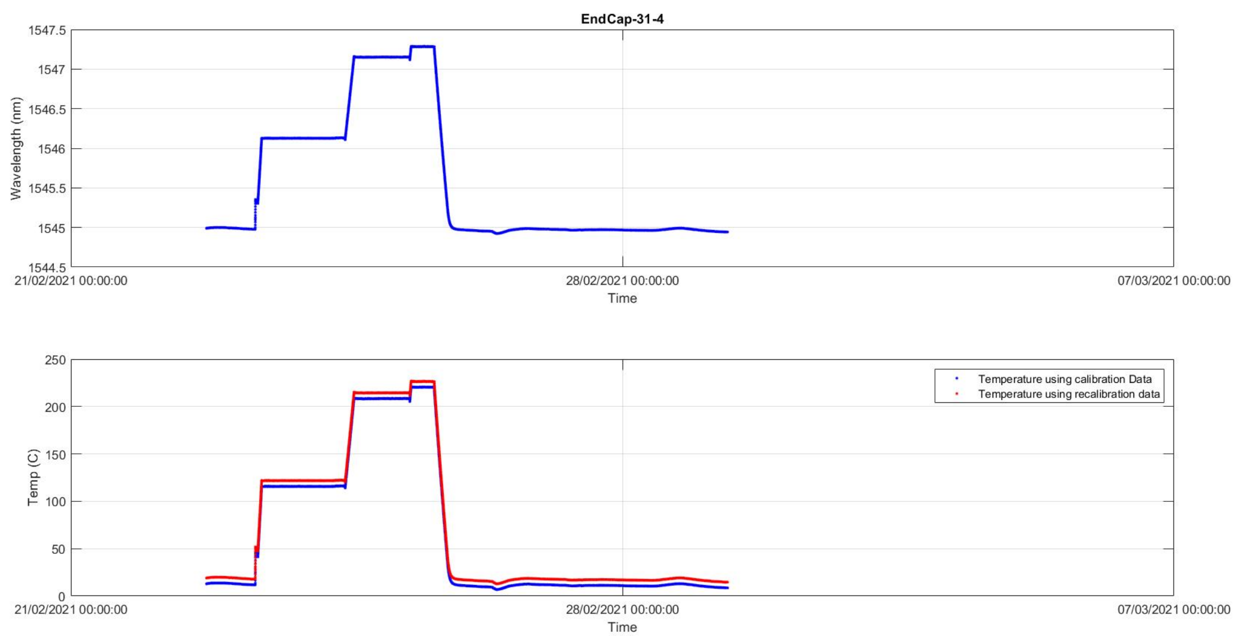

Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data
17/01/2021 00:00:00
24/01/2021 00:00:00
Time

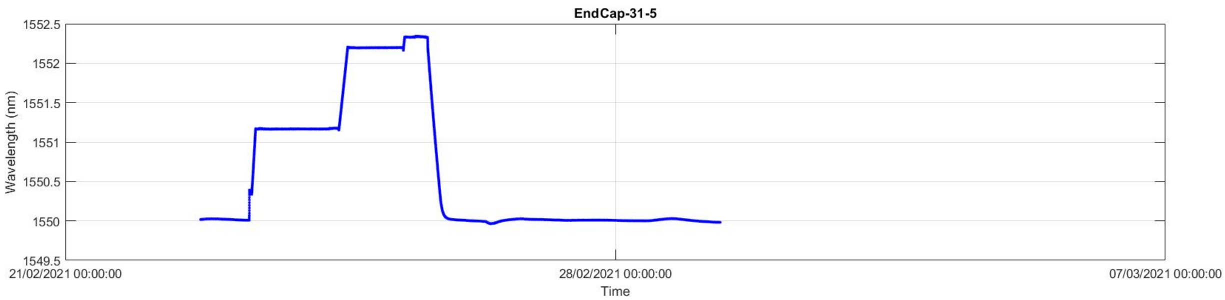
9.3.2 Endcap #1 Plots

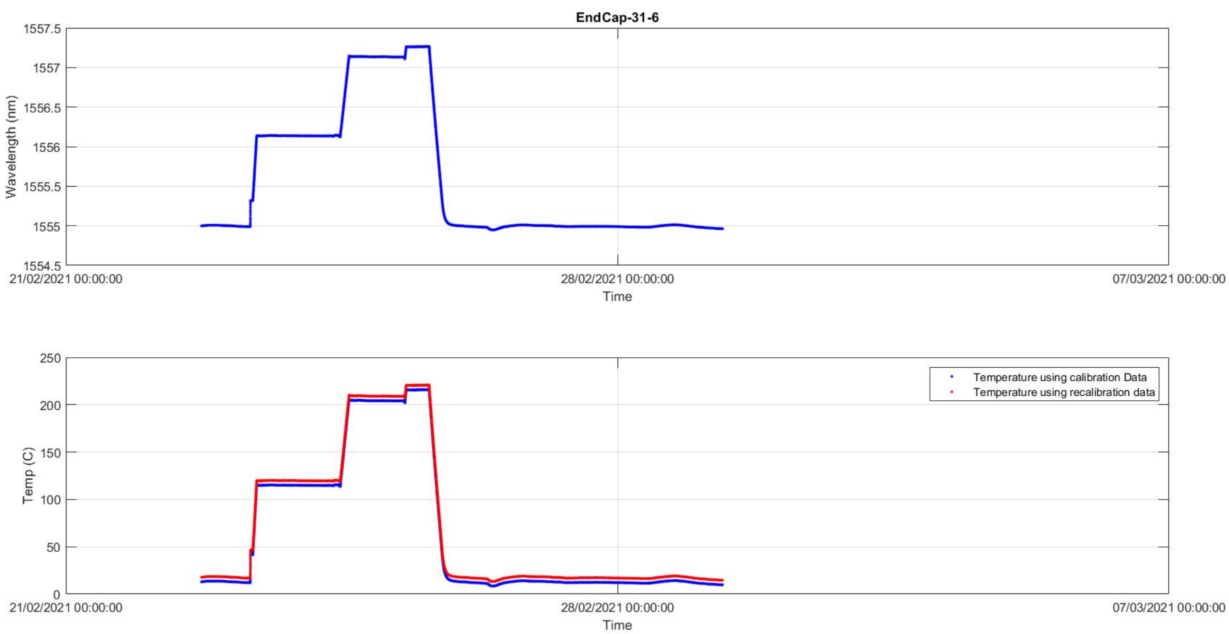


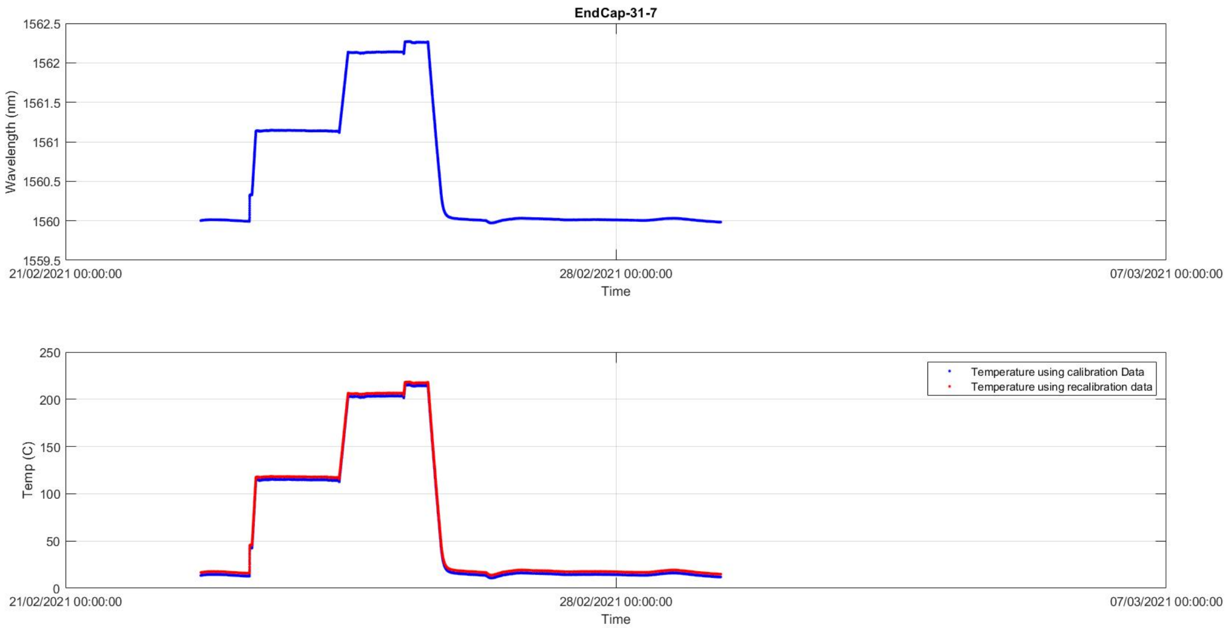



EndCap-31-3
Wavelength (nm)
1542.5
1542
1541.5
1541
1540.5
1540
1539.5
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data

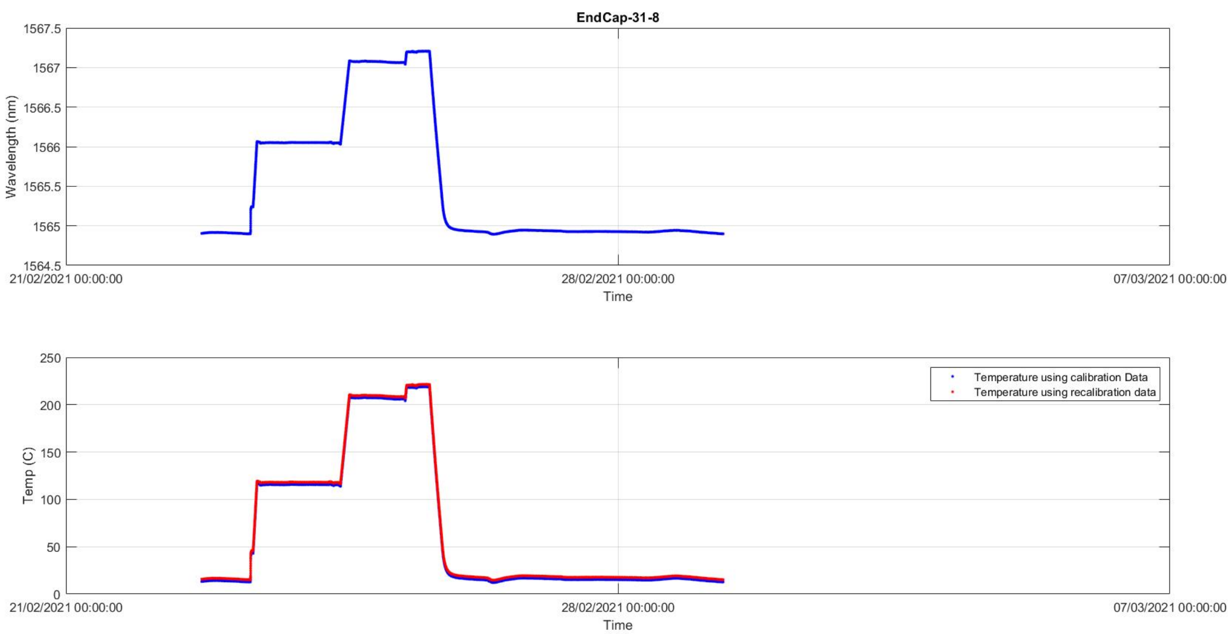

EndCap-31-4
Wavelength (nm)
1547.5
1547
1546.5
1546
1545.5
1545
1544.5
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data


EndCap-31-5
Wavelength (nm)
1552.5
1552
1551.5
1551
1550.5
1550
1549.5
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data

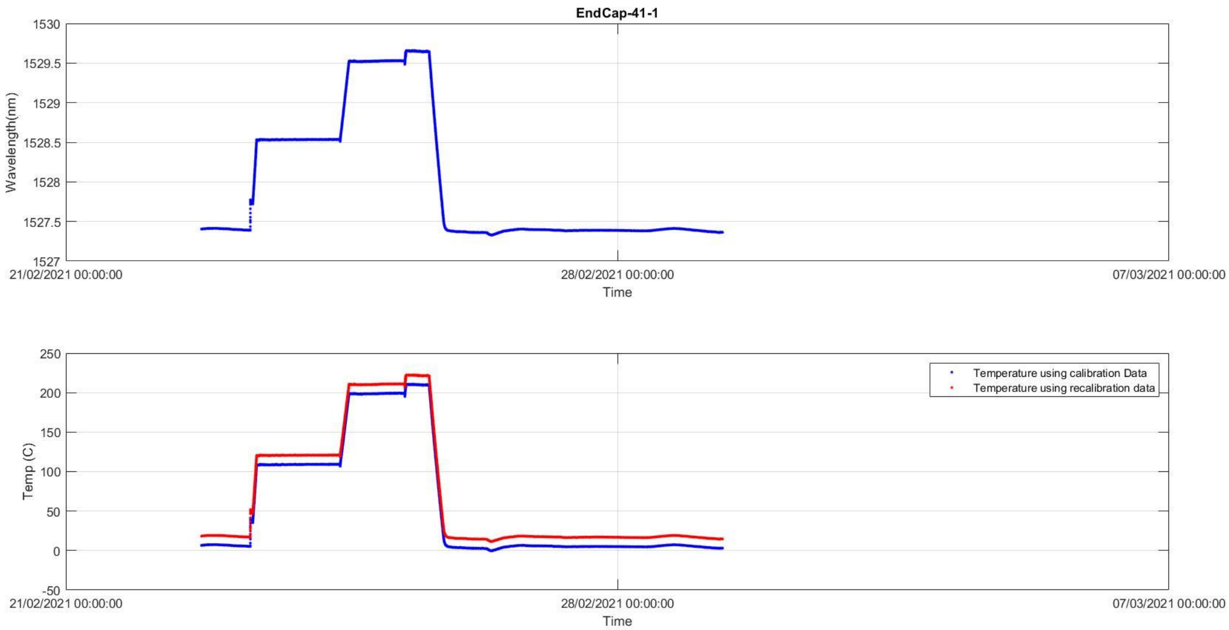

EndCap-31-6
Wavelength (nm)
1557.5
1557
1556.5
1556
1555.5
1555
1554.5
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data



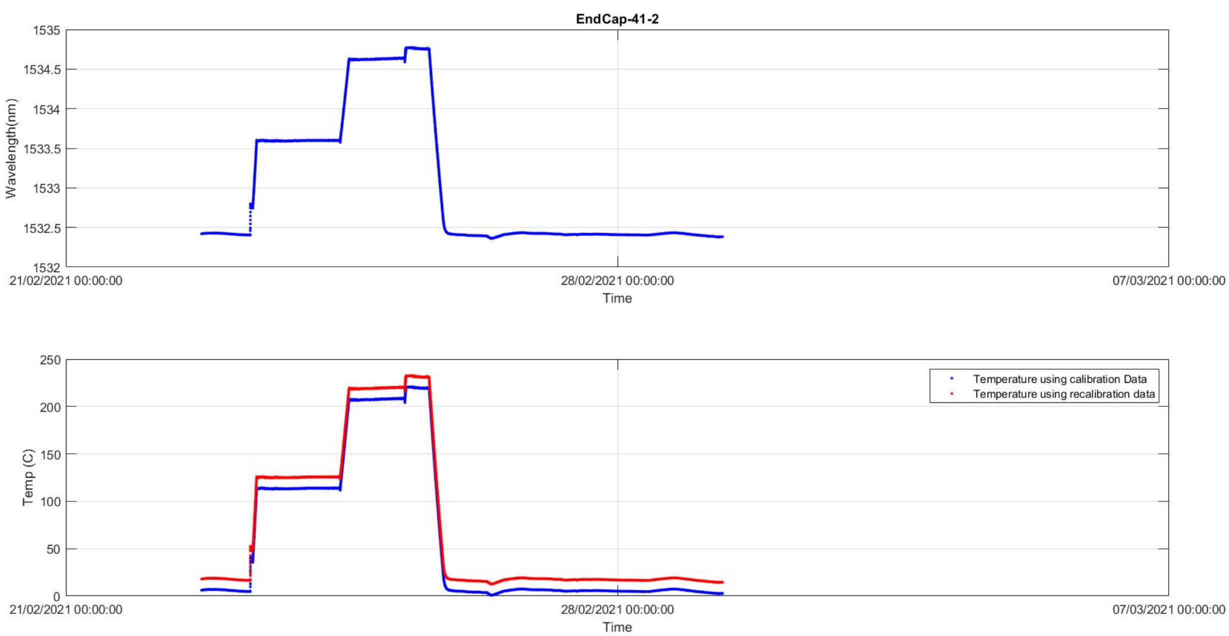
EndCap-31-7
Wavelength (nm)
Time
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Temp (C)
Temperature using calibration Data
Temperature using recalibration data



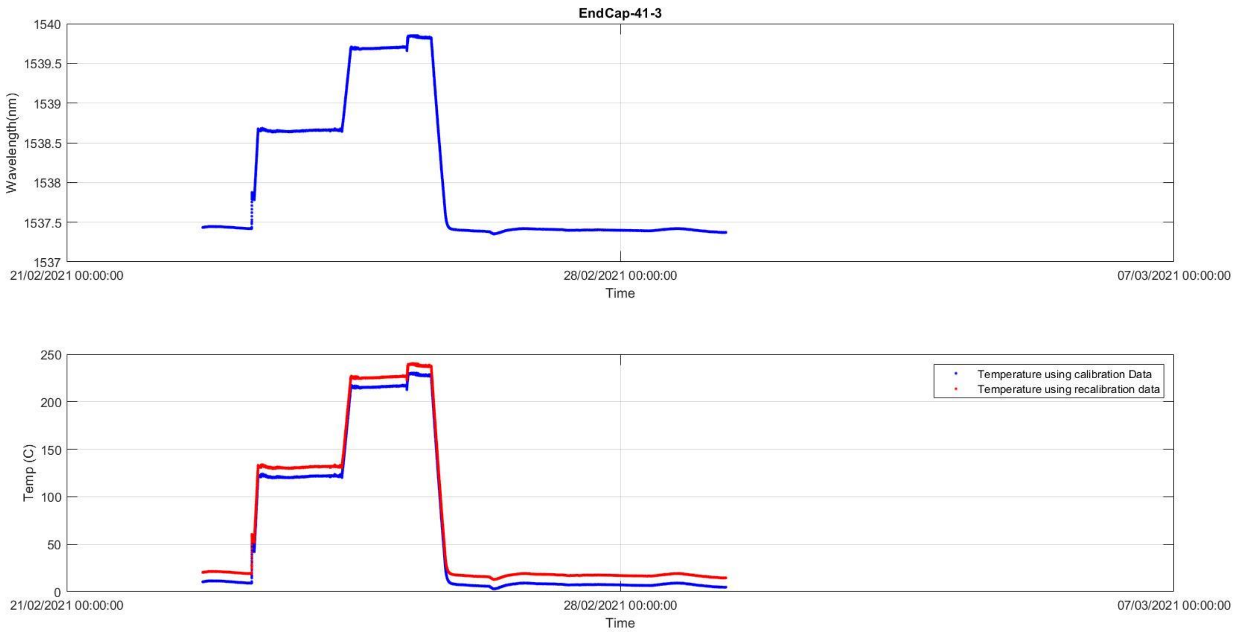
EndCap-31-8
Wavelength (nm)
Time
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Temp (C)
Temperature using calibration Data
Temperature using recalibration data

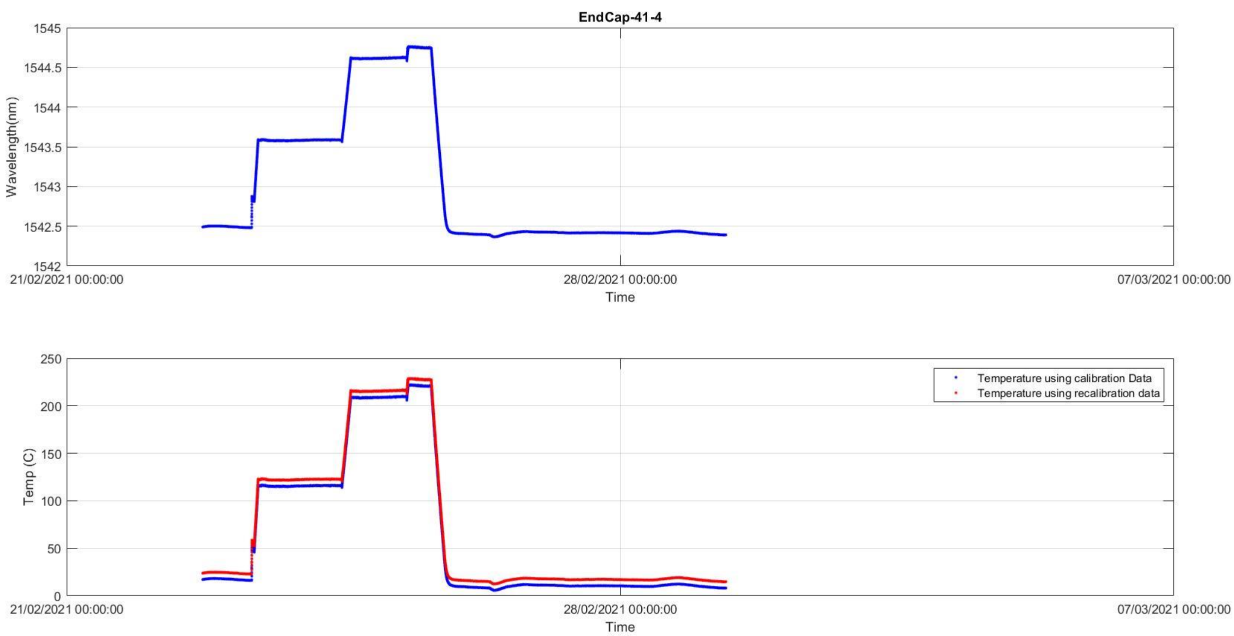


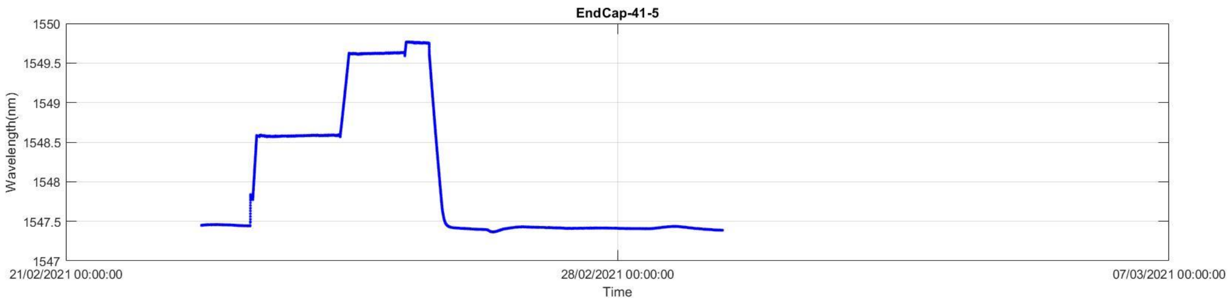
EndCap-41-1
Wavelength(nm)
1530
1529.5
1529
1528.5
1528
1527.5
1527
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
-50
Temperature using calibration Data
Temperature using recalibration data

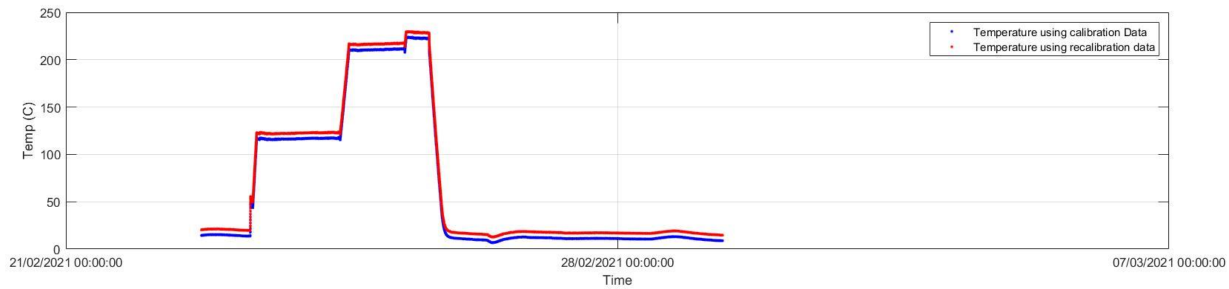


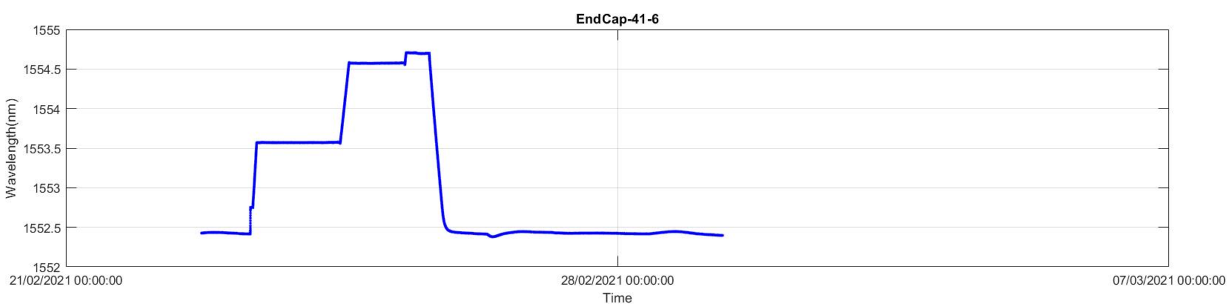
EndCap-41-2
Wavelength(nm)
1535
1534.5
1534
1533.5
1533
1532.5
1532
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data

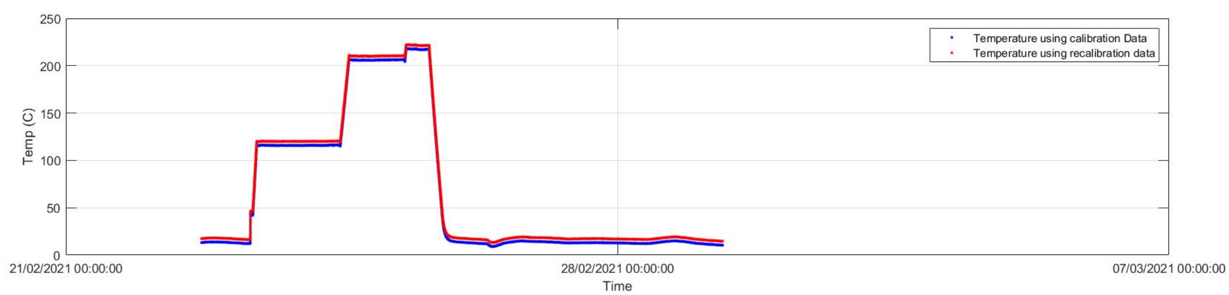

EndCap-41-3
Wavelength(nm)
1540
1539.5
1539
1538.5
1538
1537.5
1537
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Time

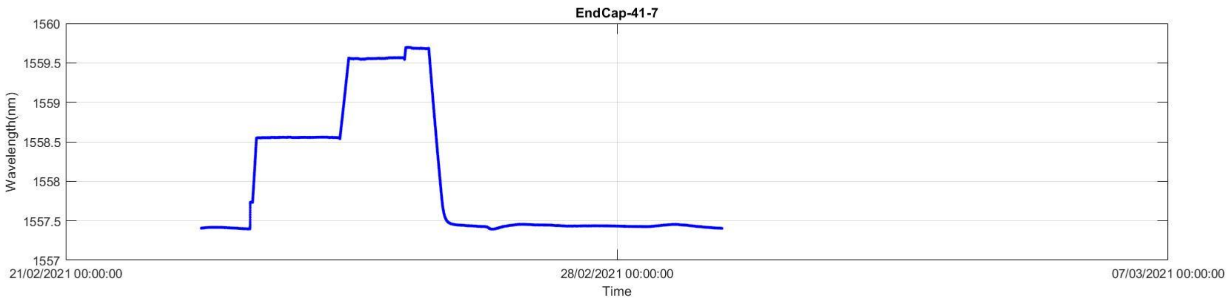

EndCap-41-4
Wavelength(nm)
1545
1544.5
1544
1543.5
1543
1542.5
1542
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Time

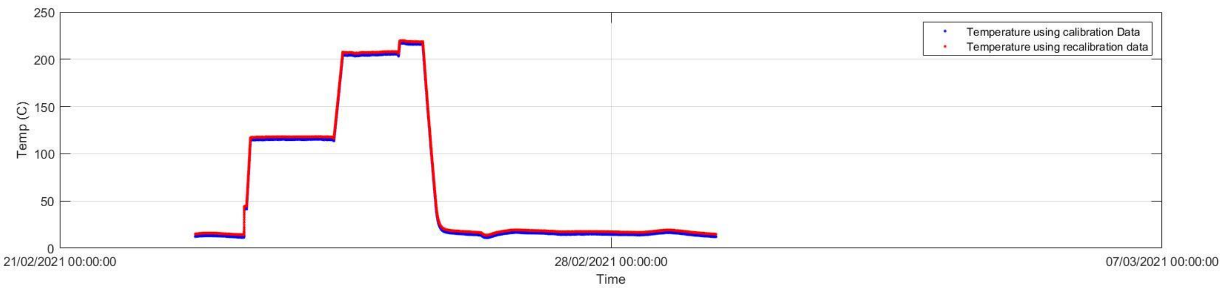

EndCap-41-5
Wavelength(nm)
1550
1549.5
1549
1548.5
1548
1547.5
1547
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Time

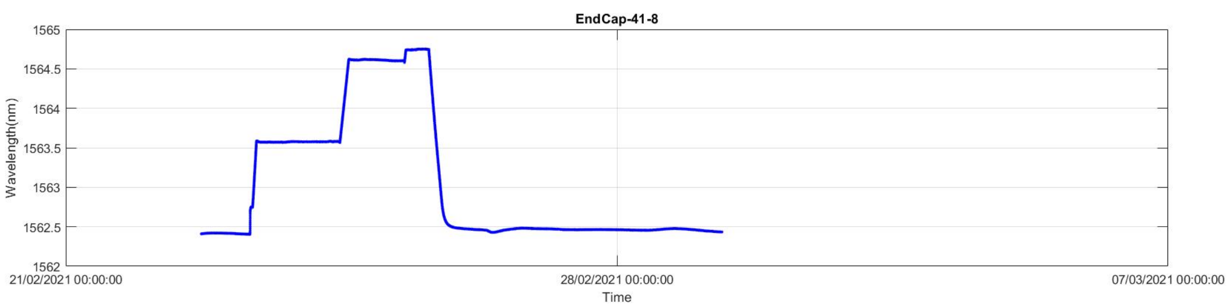

Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Time

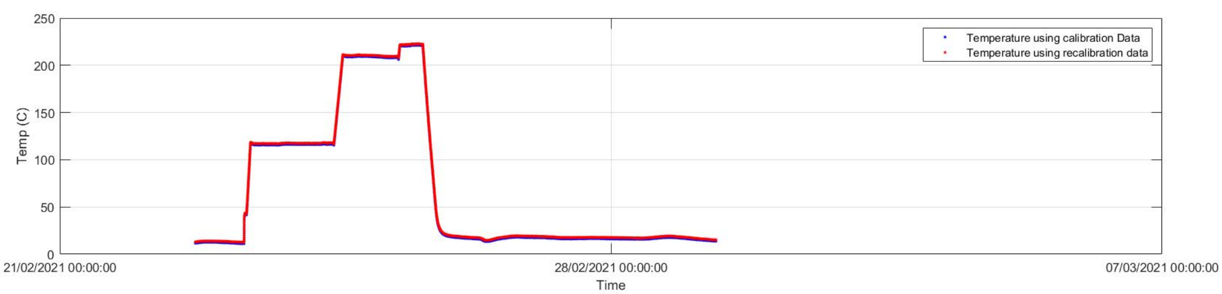

EndCap-41-6
Wavelength(nm)
1555
1554.5
1554
1553.5
1553
1552.5
1552
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Time


Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Time

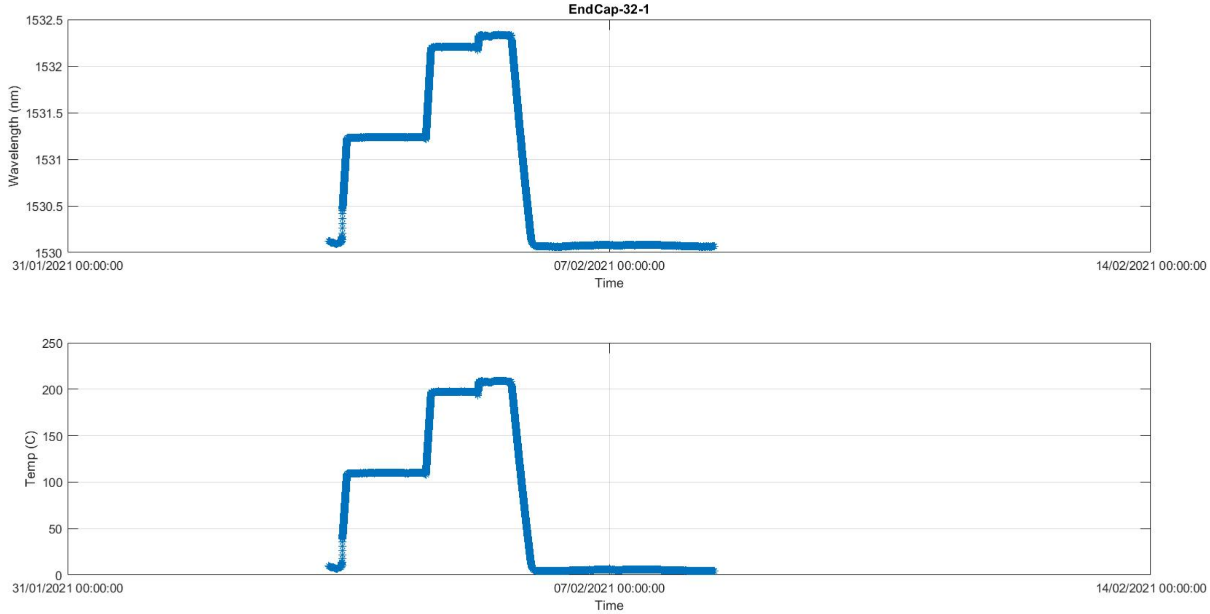

EndCap-41-7
Wavelength(nm)
1560
1559.5
1559
1558.5
1558
1557.5
1557
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Time

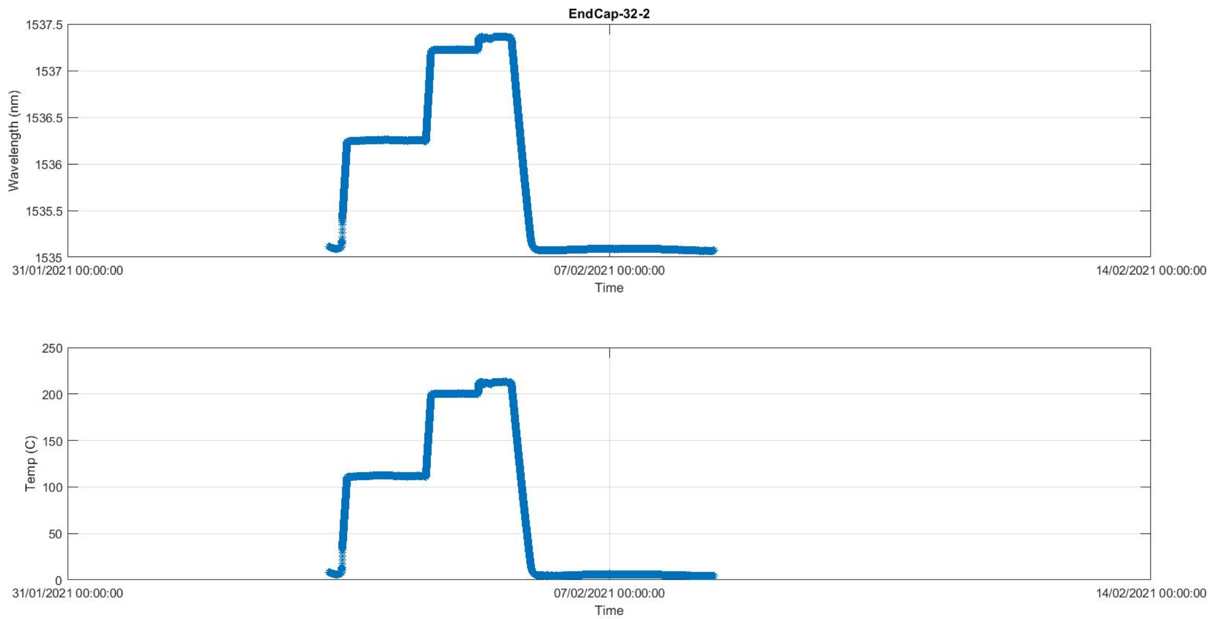

Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Time

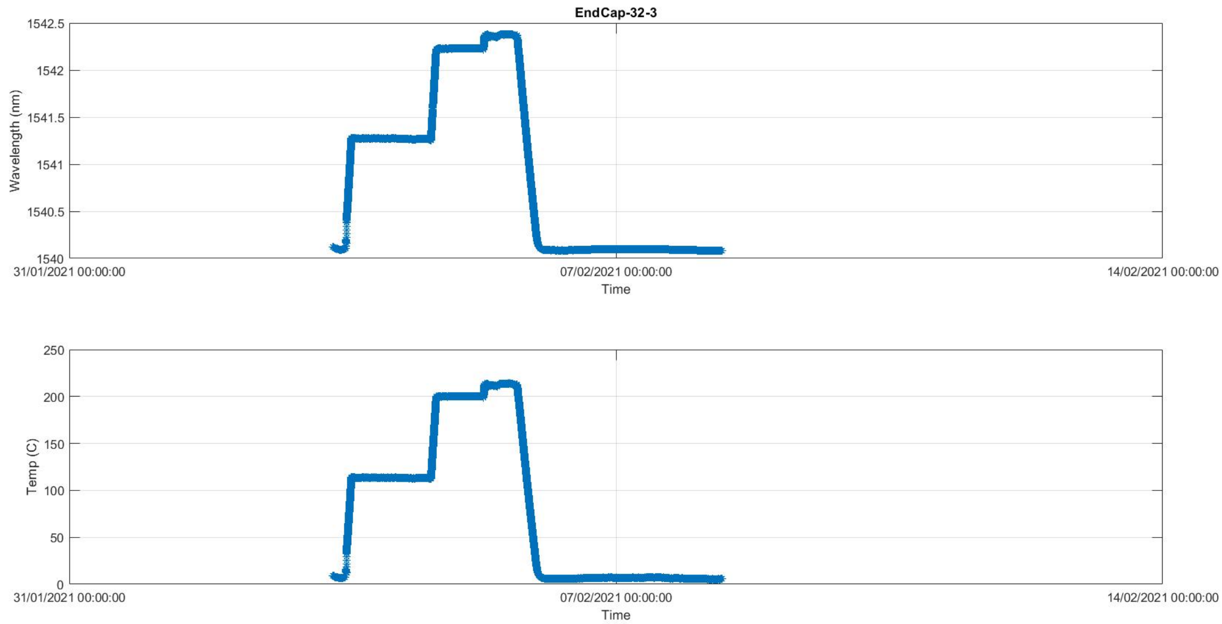

EndCap-41-8
Wavelength(nm)
1565
1564.5
1564
1563.5
1563
1562.5
1562
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Time

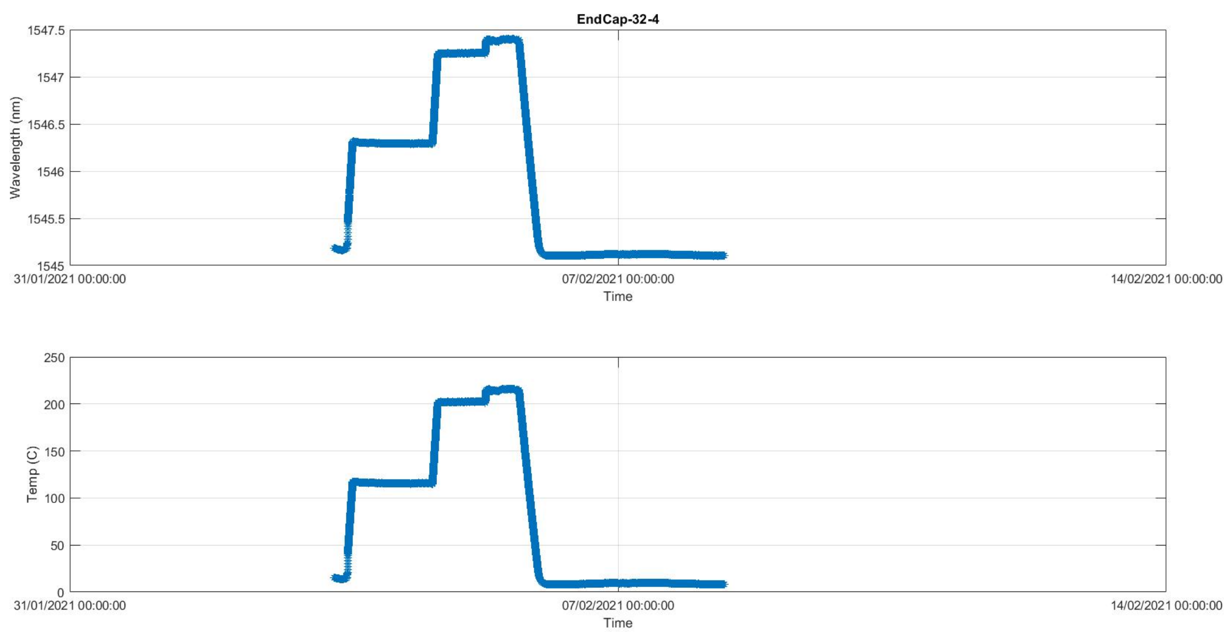

Temp (C)
250
200
150
100
50
0
Temperature using calibration Data
Temperature using recalibration data
21/02/2021 00:00:00
28/02/2021 00:00:00
07/03/2021 00:00:00
Time

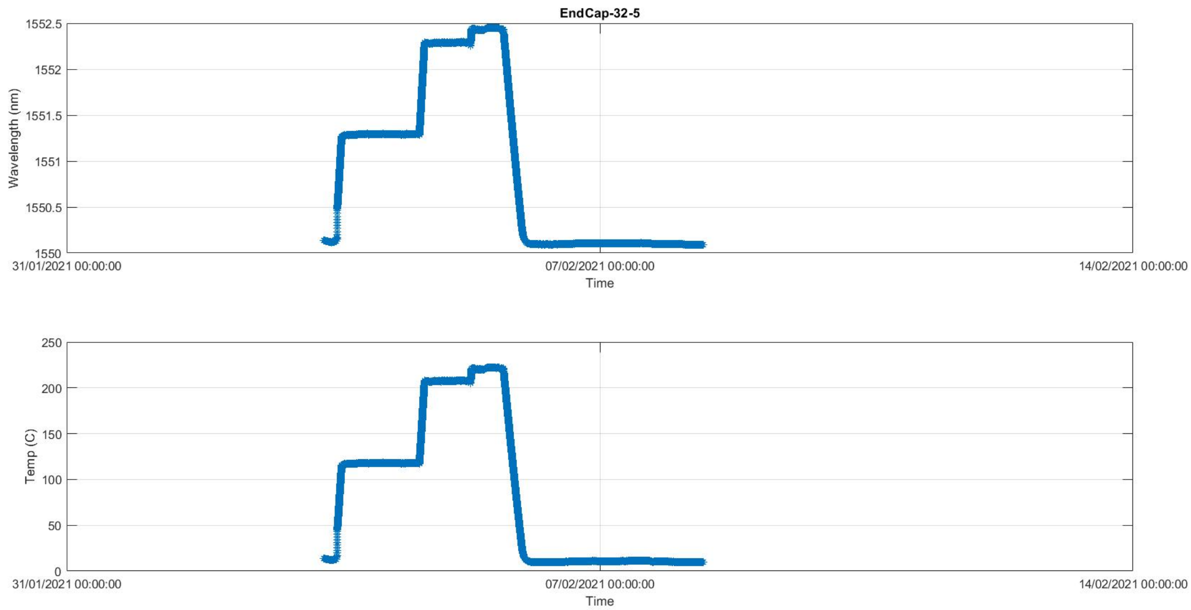
9.3.3 Endcap #2 Plots

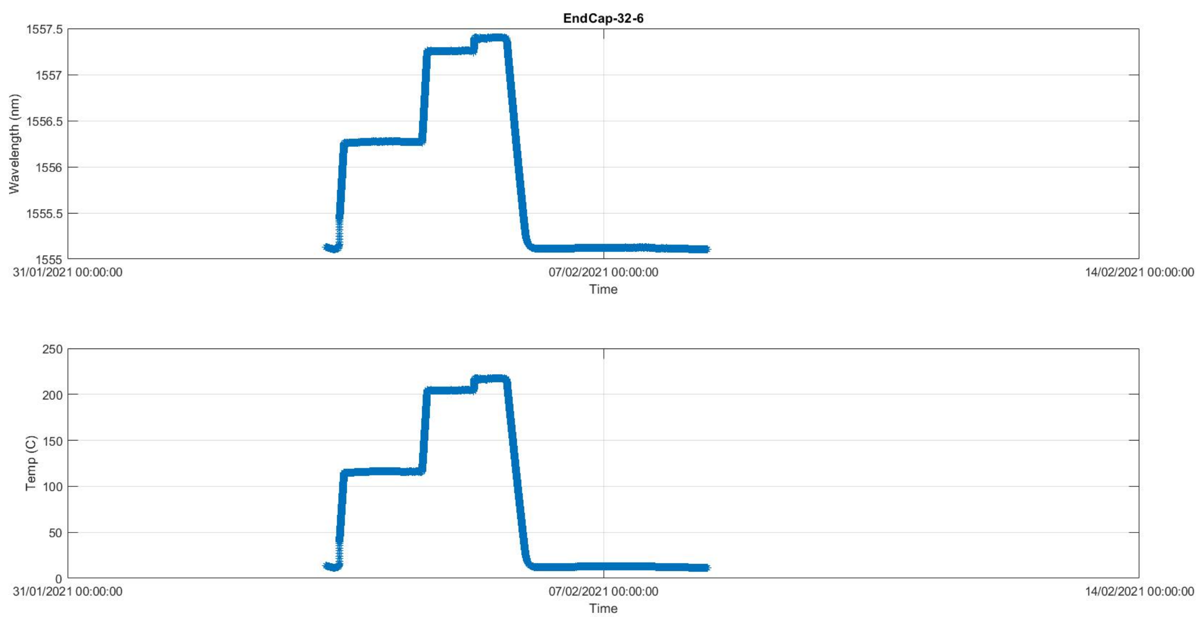


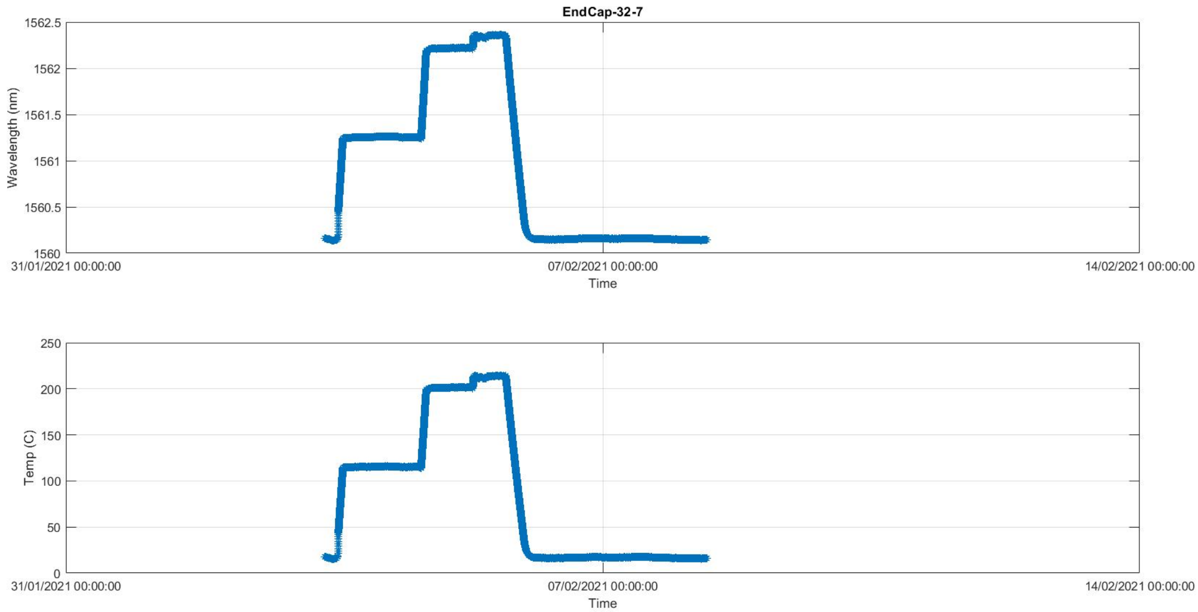


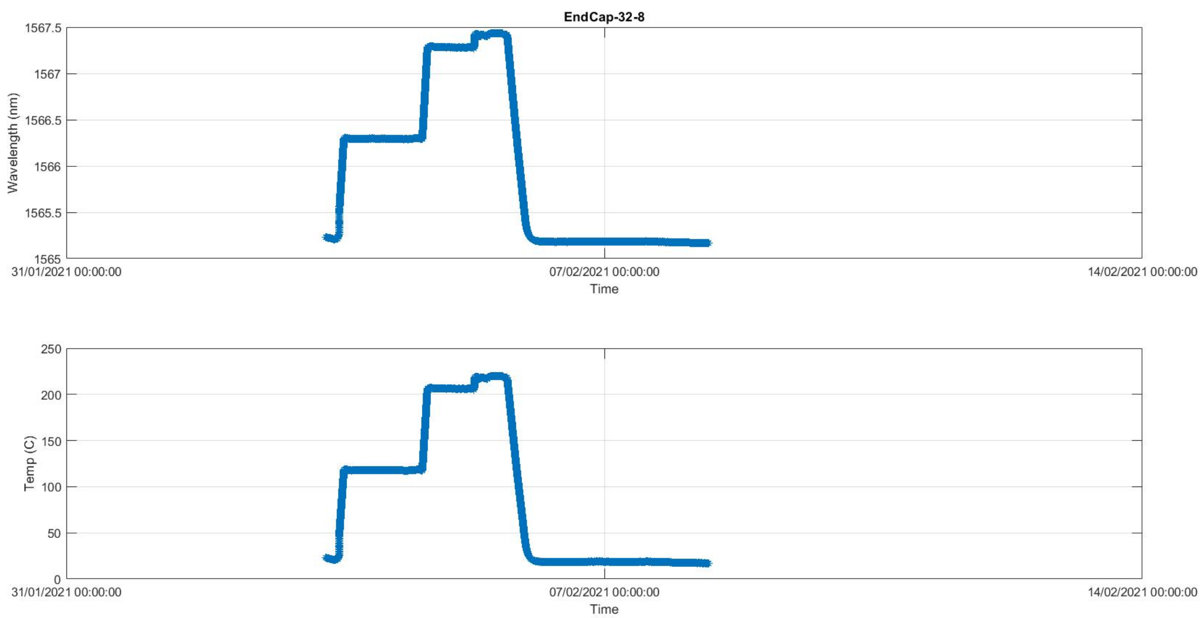

EndCap-32-3
Wavelength (nm)
1542.5
1542
1541.5
1541
1540.5
1540
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00
Time

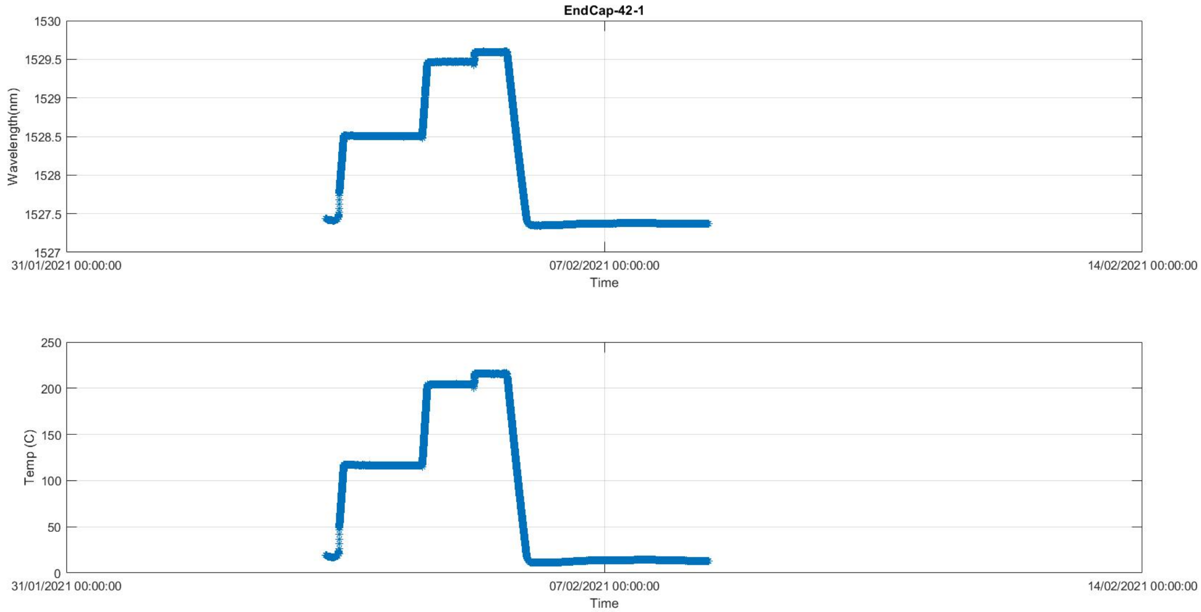

EndCap-32-4
Wavelength (nm)
1547.5
1547
1546.5
1546
1545.5
1545
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00
Time

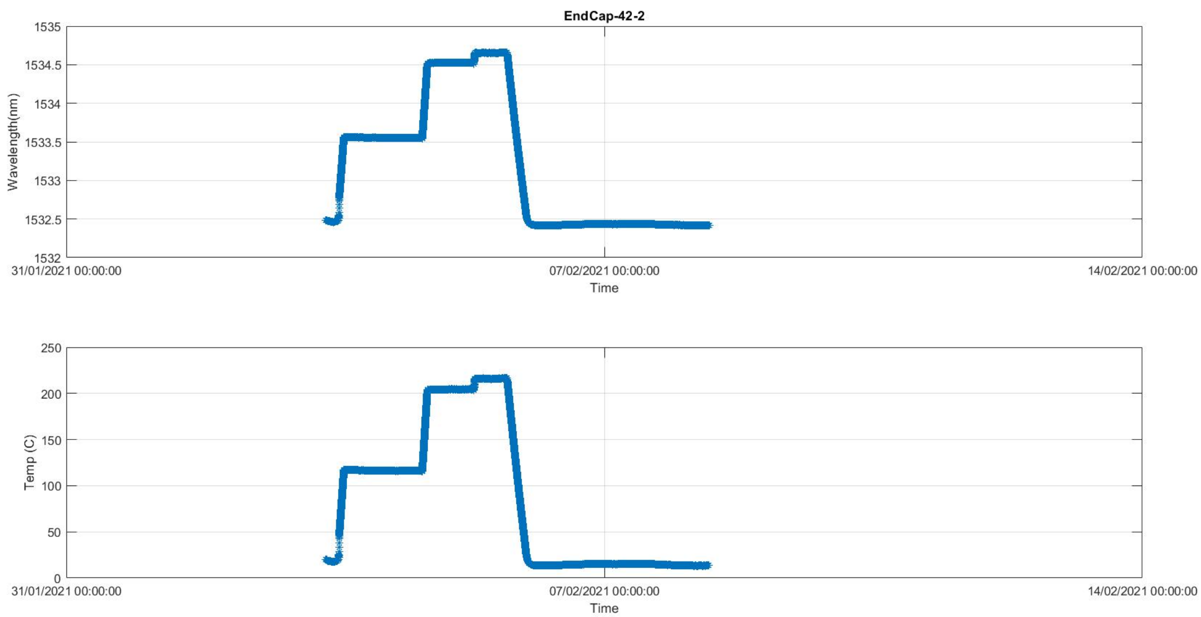

EndCap-32-5
Wavelength (nm)
1552.5
1552
1551.5
1551
1550.5
1550
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00
Time

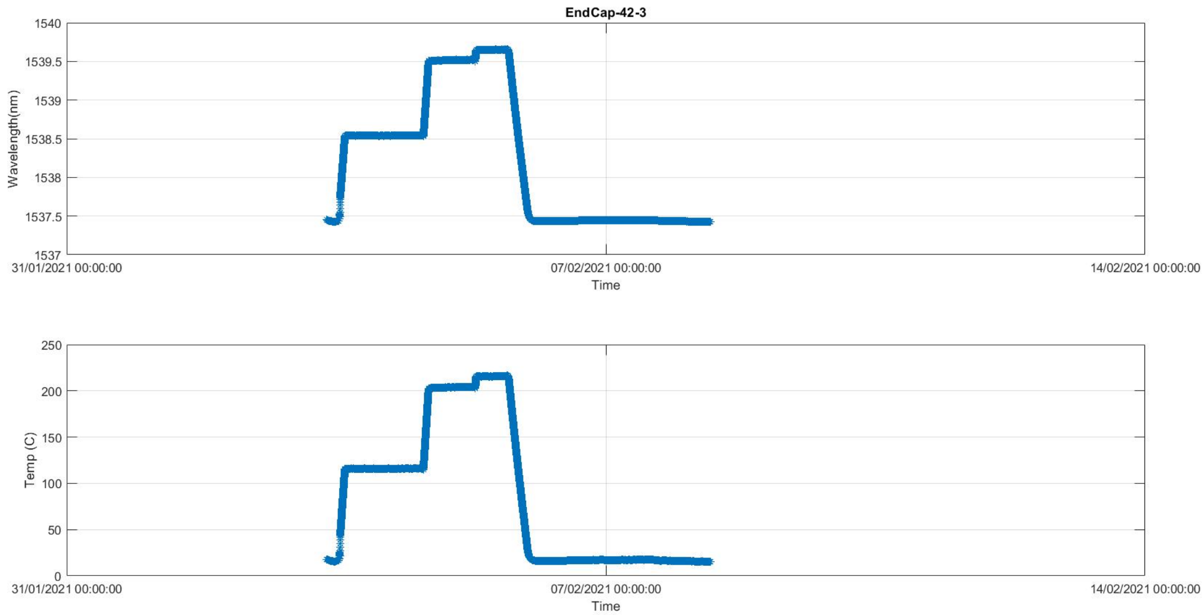

EndCap-32-6
Wavelength (nm)
1557.5
1557
1556.5
1556
1555.5
1555
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00
Time

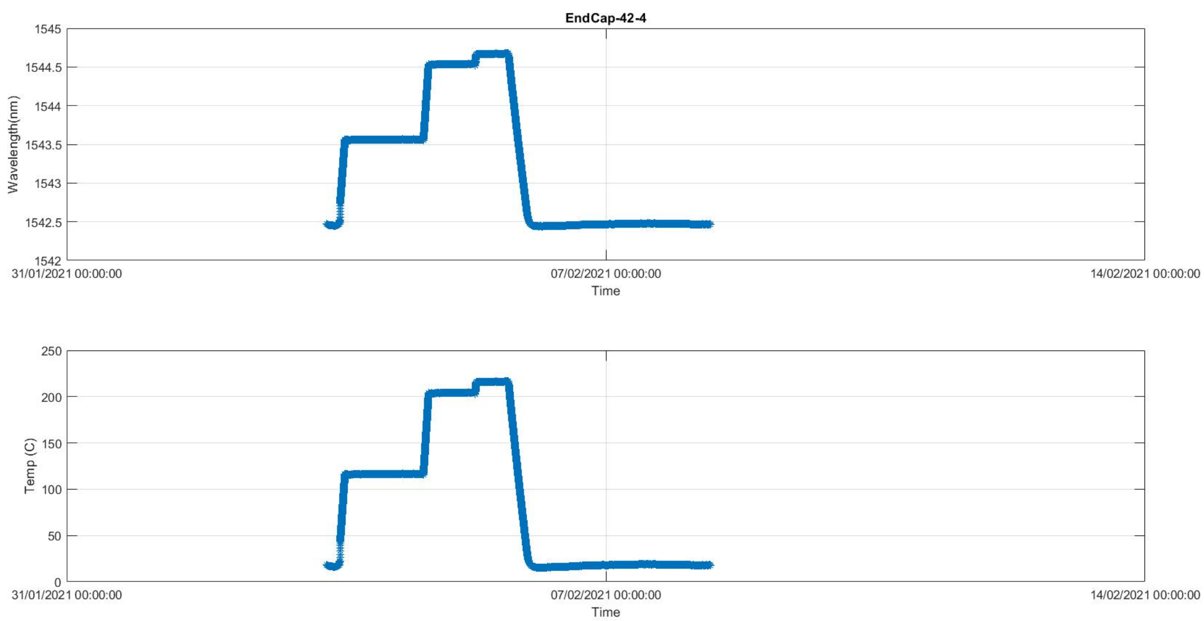

EndCap-32-7
Wavelength (nm)
Temp (C)
Time
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00

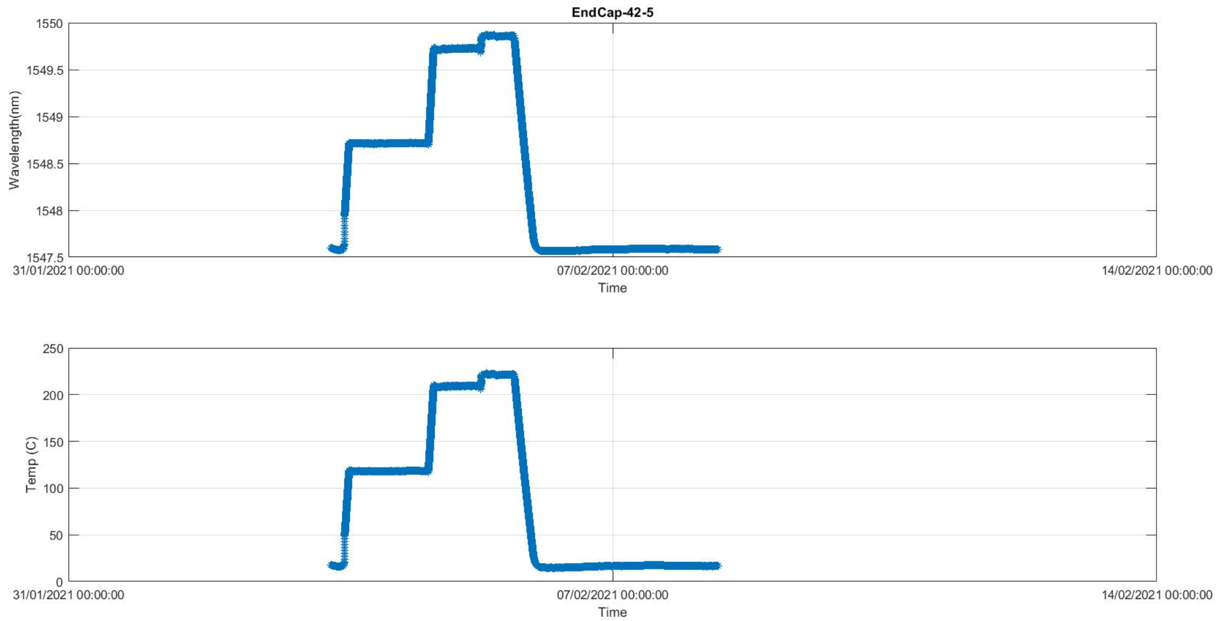

EndCap-32-8
Wavelength (nm)
Temp (C)
Time
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00

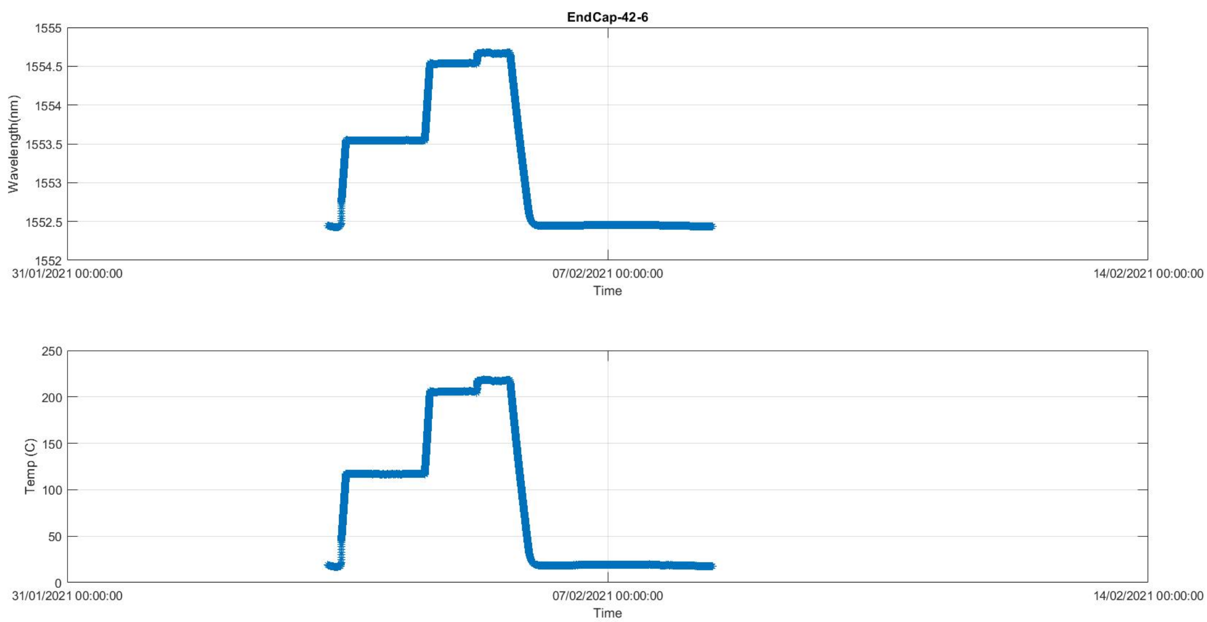

EndCap-42-1
Wavelength(nm)
1530
1529.5
1529
1528.5
1528
1527.5
1527
Temp (C)
250
200
150
100
50
0
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00
Time

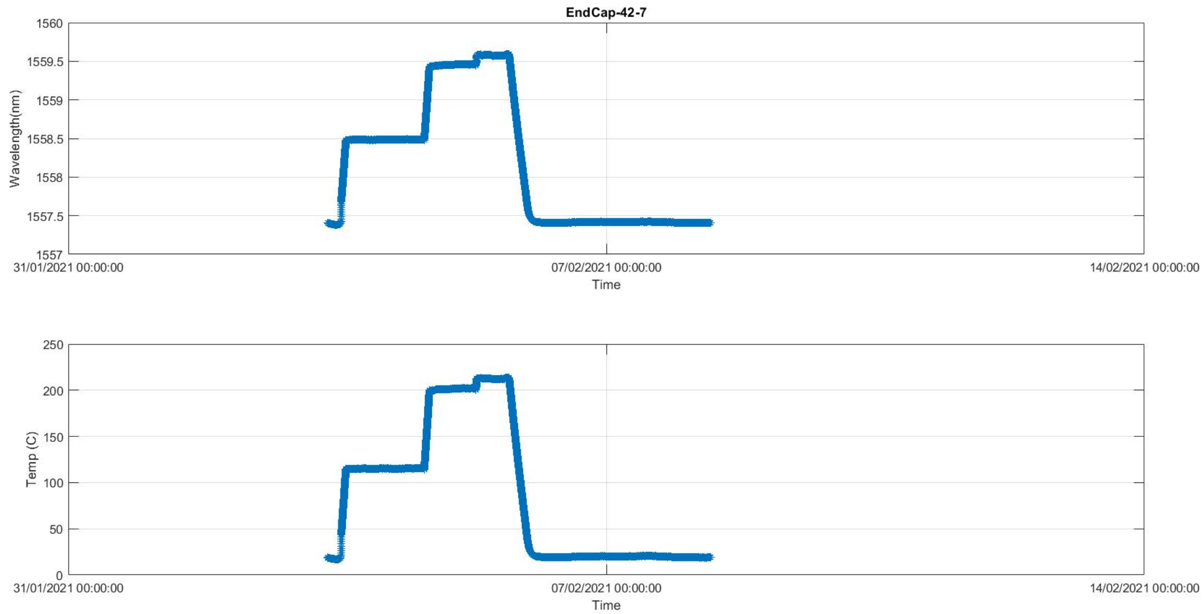

EndCap-42-2
Wavelength(nm)
1535
1534.5
1534
1533.5
1533
1532.5
1532
Temp (C)
250
200
150
100
50
0
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00
Time

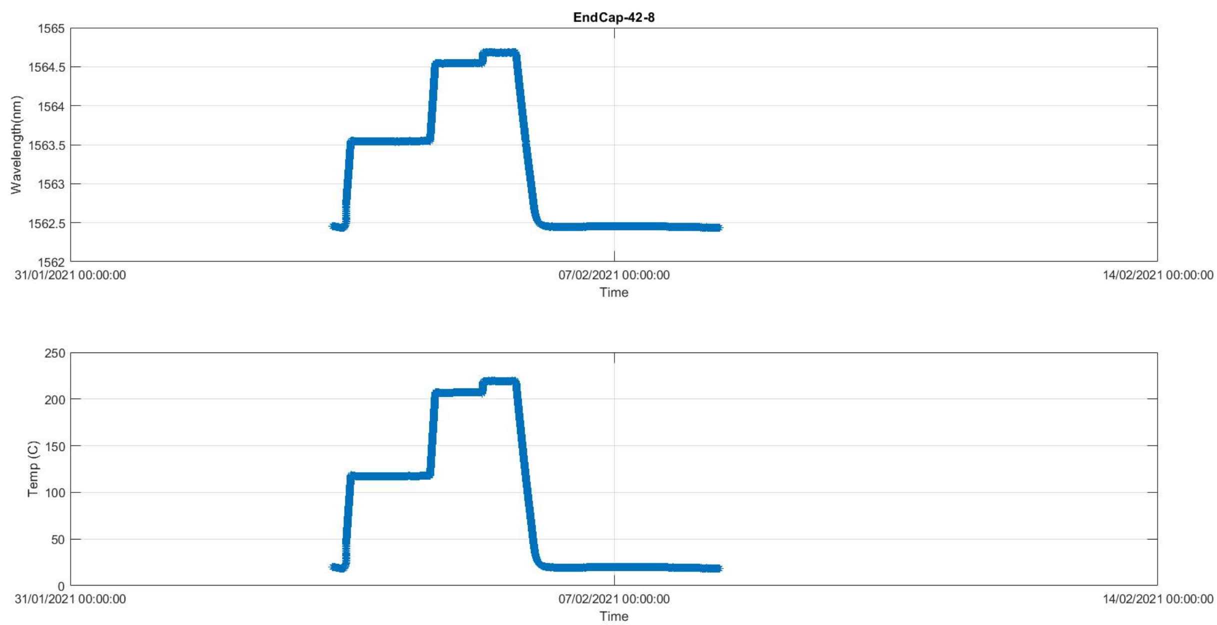

EndCap-42-3
Wavelength(nm)
1540
1539.5
1539
1538.5
1538
1537.5
1537
Temp (C)
250
200
150
100
50
0
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00
Time


EndCap-42-4
Wavelength(nm)
1545
1544.5
1544
1543.5
1543
1542.5
1542
Temp (C)
250
200
150
100
50
0
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00
Time


EndCap-42-5
Wavelength(nm)
1550
1549.5
1549
1548.5
1548
1547.5
Temp (C)
250
200
150
100
50
0
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00
Time


EndCap-42-6
Wavelength(nm)
1555
1554.5
1554
1553.5
1553
1552.5
1552
Temp (C)
250
200
150
100
50
0
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00
Time


EndCap-42-7
Wavelength(nm)
1560
1559.5
1559
1558.5
1558
1557.5
1557
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00
Time


EndCap-42-8
Wavelength(nm)
1565
1564.5
1564
1563.5
1563
1562.5
1562
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00
Time
Temp (C)
250
200
150
100
50
0
31/01/2021 00:00:00
07/02/2021 00:00:00
14/02/2021 00:00:00
Time

10 References

Fienga, F. (2017, May 3). *Innovative application of fiber optic sensors in high energy physics experiments*. fedOA. http://www.fedoa.unina.it/11832/.

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