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User Calibration of a Mid-Wave Infrared Camera for Fire Research

(Experimenting on FLIR cooled IR camera A8303sc for Actual Fire Tests)

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User Calibration of a Mid-Wave Infrared Camera for Fire Research

M. Hamed Mozaffari, Ph.D., Yuchuan Li, M.Sc., Yoon Ko, Ph.D., Mark Weinfurter

Executive Summary

Although in-house calibration is a labour-intensive task, it has many benefits of customizing the detection/temperature ranges and other parameters, suitable to a particular application. This report explains steps of undertaking in-house calibration for MWIR cameras, like FLIR A8303sc. This procedure is generalizable for other IR cameras with user calibration feature. We elaborate on all steps that we need to do for an accurate calibration. Our results of calibration have been investigated quantitatively and qualitatively in this report using comparing with actual temperature obtained from full-scale room fire tests. Also, our in-house calibrated camera was sent for the factory, and the evaluation report revealed that our calibration accuracy was in the standard tolerance range of the camera in each temperature range.

By performing this calibration procedure, we achieved the following objectives:

- Enhance the capability and competency of the Fire Safety Unit (FSU) in undertaking in-house calibrations of a MWIR camera to make it suitable for fire research.
- Acquire the knowledge of tuning parameters of IR cameras, Natural Density (ND) filters for elevated temperature ranges, and calibration using blackbodies.
- Experimentally investigate the measurement performances of different IR devices
- Validate the calibration results in full-scale fire tests.

1 Introduction

1.1 Infrared camera calibration

Any object that has a temperature more than absolute zero emits electromagnetic radiation of various wavelengths/frequencies in a continuous spectrum. The electromagnetic radiation is classified by the wavelength spectrum. Radiations with a wavelength range from 1000 nm to 1 mm [1] are called as infrared (IR) radiation. Human eye cannot detect infrared radiation, but IR cameras can convert it to a visual image that depicts thermal variations across a target object. With advance in IR imaging radiometry, commercially available IR imagers are capable of measuring the intensity of electromagnetic radiation emitted generally in the spectrum of 0.9 µm to 14 µm.

Commercially available IR detectors are the focal plane array (FPA) type that has micrometer size detector pixels made of materials sensitive to certain IR wavelengths. The material used in an IR detector is important since it determines the IR measurement methods and the wavelength that the IR detector is sensitive to. In general, based on the technology and material, IR camera detectors are categorized as thermal detectors and photon/quantum detectors [2]. Thermal detectors employ a micro bolometer, which is generally made of barium-strontium-titanate (BST), vanadium oxide (VOx), or amorphous silicon (ASi), which changes its electrical resistance in response to the thermal energy generally in Long-wave IR (LWIR) band. For the high sensitivity measurement, photon detectors are used employing materials, such as Indium Antimonide (InSb), Indium Gallium Arsenide (InGaAs), Strained-Layer Superlattice (SLS), which react to IR photons with the measurable changes of electron in their crystal structure [2]. InGaAs detectors are responsive to wavelengths between 0.9 µm and 1.7 µm which are categorized into Short-wave IR band (SWIR). InSb detectors are commonly used for measuring between 3 µm and 5 µm band, which is called Mid-wave IR band (MWIR). SLS detector can capture in a wider range of wavelength from 7.5 µm to 10.5 µm, called Long-wave IR band (LWIR). InSb and SLS detectors must be cooled to cryogenic temperatures for proper functioning [2]. For this reason, cameras equipped with these two detectors have a closed-cycle Stirling cryocooler like a refrigerator that uses helium gas for cooling.

IR radiation emitted from an object in the scene is mapped by the lens onto the IR detector, and then converted into an IR image. Hence, the IR image will provide a two-dimensional map of IR radiation emitted by the object. One of the main applications of IR camera is to record IR images to see the temperature distribution of an object in the scene. However, the IR generated image data is in units of digital counts which is the output of camera analog to digital (A/D) circuit. In order to convert the radiation count image/map into temperature, we need to find a relationship between radiation count and temperature that it is known as radiometric calibration. Hence, every pixel in an IR image is formed only by a radiometrically calibrated camera.

1.2 Objectives of in-house calibration

In calibration of these IR cameras, it is important to understand not only their detector technologies but also the measurement responses with different optics and filters, as well as on the undergoing application. In the application to fire and flames, calibration should be completed using specific optical filters depending on the measurement purposes and the target temperature range.

In general terms, calibration of a thermal IR camera is the process of defining the relationship between infrared radiations that the camera sees and known apparent temperatures. Usually, cameras are calibrated in advance in factory for specific temperature ranges, and the calibration should consider many factors and parameters, which might affect the measurement. Nevertheless, the user might need to use the camera for temperature ranges outside of the provided factory calibrations. Furthermore, due to the camera's detector, sensor, and electronic components aging over time, the currently available factory calibration might not be accurate anymore, and the camera captures images with inaccurate temperatures. In these situations, based on the features and specifications of thermal cameras, users can perform in-house calibration when factory calibration is not ideal. In-house calibration would allow users to fine tune some of the parameters focusing on the application of interest. Also, in-house recalibrations allow users to optimize a few of those parameters and recalibrate the thermal. Note that the actual surface temperature is different from the apparent temperature.

This report aims to provide overall understanding of IR cameras and in-house calibration setup/procedures as well as calibration evaluation in application to fire.

The main goal of our calibration is explaining the steps and terminologies for performing in-house calibration of MWIR FLIR A8303sc camera in order to capture images of fire ignition, flame and smoke growth, and monitoring flashover with temperature ranges from ambient temperature up to 2000°C. Based on the availability of various blackbodies, specification of camera, and correct setting of camera parameters, the accuracy of calibration has a tolerance of around ±2% or ±2°C. The tolerance of calibration can be found in the comparison report we received from FLIR Company after calibration of our camera (See Appendix A).

2 Understanding camera technologies for calibration

This section provides, brief fundamentals of infrared camera technologies and important terms which are used in this field for usage and calibration of thermal infrared cameras.

2.1 IR Cameras

Infrared is part of the electromagnetic radiation spectrum (see Figure 1). All objects with a temperature above the thermodynamic absolute temperature which is -273°C or 0°K emit infrared radiation. Figure 1 also shows the impact of atmosphere on the transmission of infrared radiation. Figure 2 shows the IR spectrum divided into NIR, SWIR, MWIR, LWIR, and VLWIR.

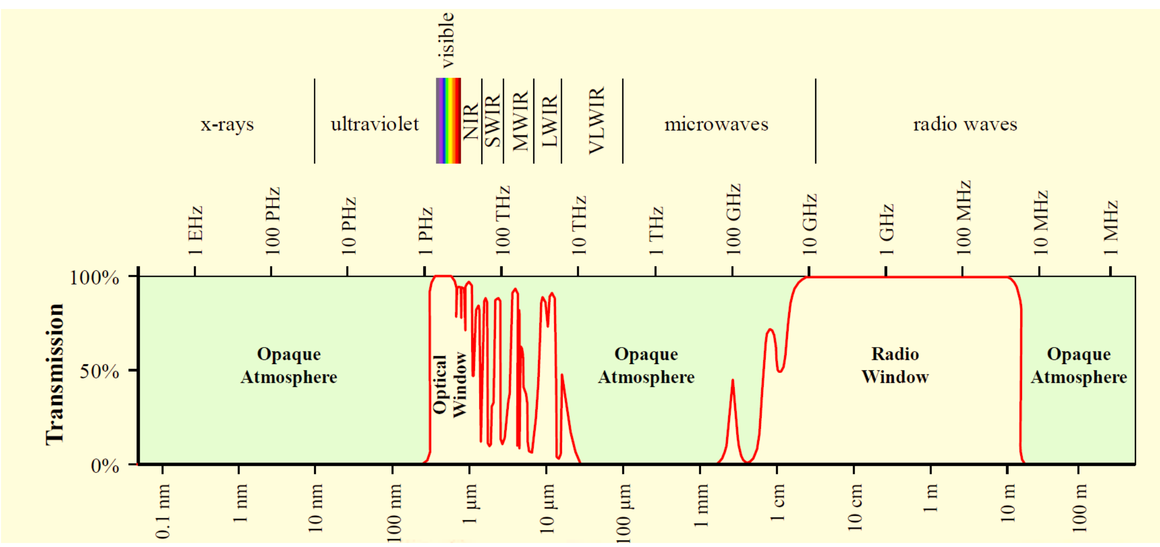


Figure 1. Electromagnetic radiation spectrum. (Image modified from [3]**).**

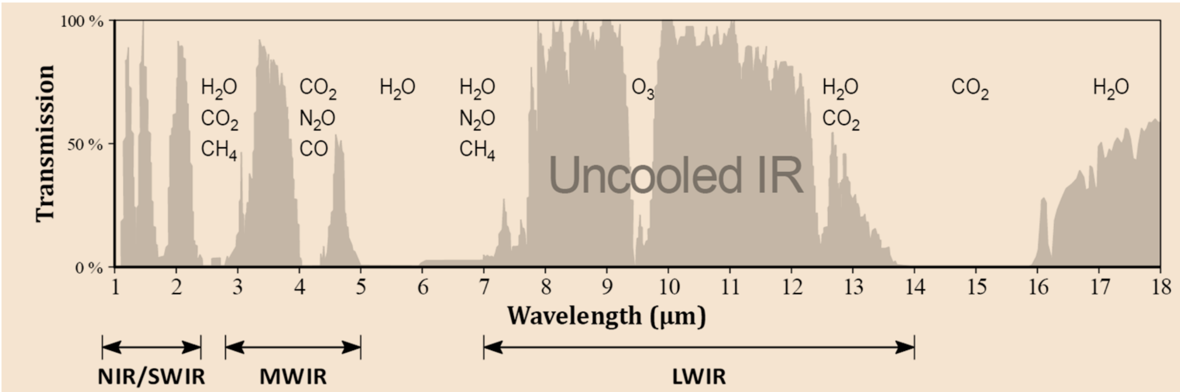


Figure 2. Zooming on the infrared part of the electromagnetic spectrum. (Image modified from [4]).

Infrared imaging usually refers to the two of these regions: MWIR and LWIR or far-infrared imaging. Based on these two regions, often, infrared detectors embedded into IR cameras are divided into two categories of cooled and uncooled sensors, respectively. Infrared radiation energy emitted by an object is received by an optical system attached to the detector. The detector converts this energy into electric signals for the electronic components of the camera, where after image processing, one infrared thermal image is generated. Main characteristics of infrared imaging technology are non-destructive and non-contact detection.

IR camera detectors are categorized as thermal detectors and photon/quantum detectors. Thermal Infrared (IR) imaging cameras (sometimes called TIC) are becoming an essential tool for firefighters and first responders. These cameras can provide firefighters and first responders with critical information to locate/rescue people in fire incidents as well as analyse the status and the intensity of the fire for decision making and selecting an appropriate suppression strategy. Photon/quantum detectors requiring cooling processes due the measurement sensitivity.

In general, in choosing thermal IR cameras, one should consider the IR radiation wavelengths based on the detector technology, measurement temperature range, as well as the image resolution and field of view which are based on optics and detector size, software features such as user calibration, super-framing, recording formats, portability and power consumption, and more importantly the application type of the camera such as fire safety, surveillance, or research and development (science) version. Also, other considerations are the frame rates of video recording and integration time of the camera, thermal sensitivity which defines the smallest temperature difference a camera can detect. In this section, these factors will be explained in more details.

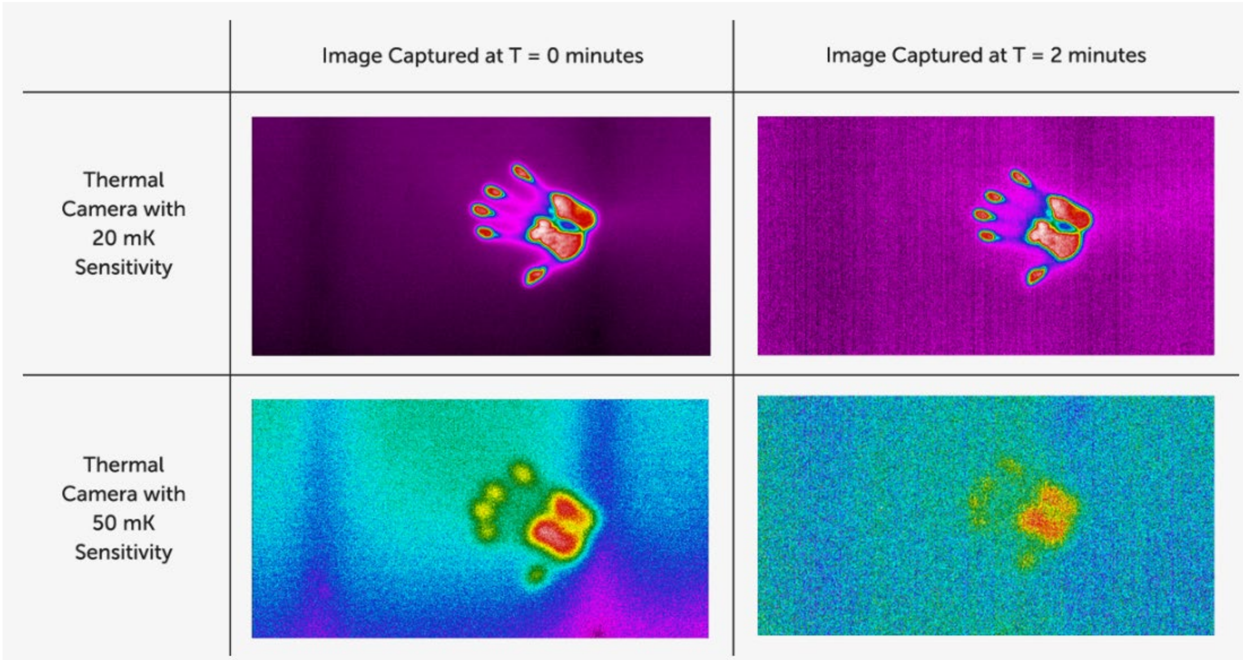


Figure 3. 20 mK versus 50 mK sensitive thermal sensors of a handprint at time zero and two minutes. Image from FLIR TELEDYNE company [5]**.**

2.2 Cooled MWIR camera

As mentioned before, IR cameras or (also known as thermographic cameras) can be broadly divided into two types of cooled photon detectors (counting incident photons) and uncooled thermal detectors (measuring the electrical resistance in response to the thermal energy).

IR cameras with a cooled sensor provide distinct advantages in comparison to a thermal IR camera with an uncooled sensor. The cooled thermal cameras capture infrared energy generally in the 3 µm to 5 µm infrared spectrum, while uncooled cameras capture generally in the long range of 7.5 to 13.5 µm. Inside a cooled IR camera, a detector is integrated with a cryocooler (i.e., small refrigerator), which makes the sensor temperature cool to cryogenic temperatures. This cooling process is essential to reduce thermally-induced noise to a level below that of the signal from the target object whereby the thermal sensitivity of the camera is significantly improved. In other words, sensor cooling solves the impact of the heat that is emitted from the camera itself. The detector of IR cooled cameras are designed to count photons from the target using photodetectors which are designed based on a wide range of narrow gap semiconductors. Popular semiconductors for detectors are Indium Antimonide (InSb) for 3-5 µm or MWIR band, Indium Gallium Arsenide (InGaAs) for 0.9-1.7 µm or SWIR, and Strained-layer Superlattice (SLS) for LWIR (7.5-10.5µm). The InSb and SLS sensors must be cooled to function properly while InGaAs can also work in room temperature.

Cooled IR cameras are preferred for imaging infrared radiation of objects, since the high thermal sensitivity less than 20 mK. One great benefit of the cooled IR cameras is that due to the shorter wavelength (3 to 5 µm) in comparison with long range of uncooled cameras (7.5 to 13.5 µm), the thermal resolution of the cooled camera is generally higher in particular for the elevated temperature region, so that users can see details and farther details using appropriate lens. Also, there are other unique features which can't be achieved by uncooled ones, such as high frame rates. However, in general, cooled cameras are relatively large in the size and power consumptions. Also, the mean time to failure (MTTF) of the cooled camera is known to be short due to the delicate mechanical components working inside the camera for cooling purposes as well as potential deformation due to the extreme change of temperature.

In application to fire/flame, seeing through hot combustion effluents/flame can be accomplished by using spectral band-pass filters (e.g., a 3.88-3.92 µm narrowband see-through-flame filter), which filter out the spectral bands with attenuation due to gas-phase absorption or emission caused primarily by the presence of carbon dioxide and water vapour. On the other hand, when imaging flame/fire, generally MWIR cameras are suitable because the intensity differences between a flame and its background is more distinct in the MWIR band than the LWIR band, in particular when a flame is nearby hot objects. Also, the MWIR band is usually considered as the most suitable range to study flame and combustion since many combustion products, such as water vapour, carbon dioxide, carbon monoxide and hydrocarbons are infrared-active in the MWIR band. The LWIR band of 8 to 14 µm is also aimed for firefighting thermal imaging cameras, because in the band, the radiance absorbance by soot and water vapour are relatively low, and the energy from solid surfaces is radiated. Figure 4 illustrates one example frame recorded by MWIR (FLIR A8303sc) and LWIR (FLIR T650sc) cameras. From the figure, it can be seen clearly that MWIR camera focused and provided more detailed image about the flame, particles, and partly smoke regions while the LWIR image is more emphasised on the radiation on the surfaces and reflections. Note that these differences are not sharp, and both technologies are sensitive to radiation of flame, smoke, and surfaces, but each technology has its own capability better than the other.

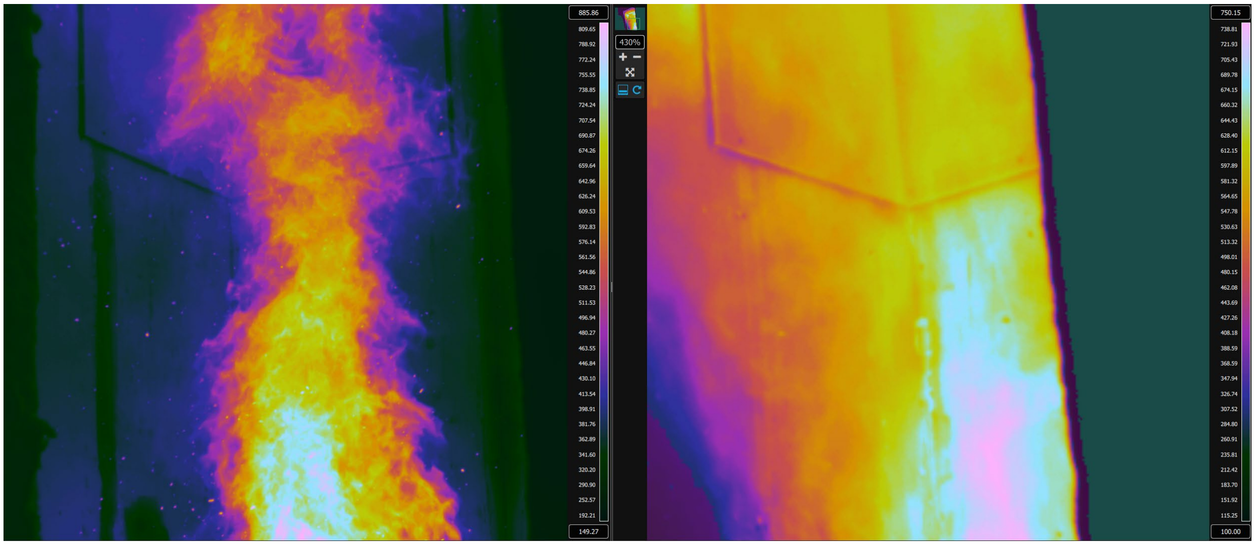


Figure 4. The differences between MWIR (left image) and LWIR (right image) for approximately the same angle of view and time.

2.3 Optics and Lenses

Infrared radiation can't pass regular glass used in RGB cameras. For this reason, lenses of IR cameras are made from different types of materials which are opaque for visible cameras. Typical materials used for IR lenses are Silicon (Si) and Germanium (Ge). The Si lenses are more used for MWIR cameras whereas Ge lenses are used for LWIR cameras. The lenses of IR cameras have antireflective coatings similar to visible light cameras. Transmission of IR lenses based on their quality and design is around 99%. The functionality of optics and lenses in IR camera is out-of-scope of this report. However, as a basic principle, the distance from the location that IR radiation converged to map on the detector (i.e., focal plane) to the center of lens glass is called focal length. As a rule of thumb, the longer the focal length of a camera, the farther distance we can see, yet with the cost of a smaller field of view (FOV). Typical IR lenses have a focal length (indication of zooming ability) from 50 mm to 1200 mm. Most common used lenses are 17 mm, 25 mm, 50 mm, 100 mm, 200 mm, and 1X to 4X zoom lenses. A 4X magnification makes little sense in the longwave IR band, as there will be far too much diffraction blurring to make use of the magnification. The focal point of each lens can be adjusted manually or automatically based on the camera lens features. In general, each lens has a unique field of view (FOV) depending on its focal length. The farther we can see with the camera, the smaller the FOV becomes.

Similarly to RGB cameras with an aperture controlling the light intensity, the thermal/photon count cameras have an aperture/cold shield to control the intensity IR radiation coming to the lens. The f/number of the shield is defined by the ratio of the focal length to the aperture size, and the higher the f/number is, the less IR radiation will reach to the sensor. The details of these optic parameters are out of scope of this report. Yet, as an example, a MWIR camera with f/4 lens can view a higher temperature target without saturation as compared to the same lens (with the same integration time) but with f/2.5 cold shield. Therefore, it is possible to calibrate f/4 cold shield MWIR cameras to temperature higher than 350°C.

The IR camera lens can be coupled with filters for blocking/transmitting of certain wavelengths. Neutral Density (ND) filters are also used to limit the intensity of IR radiation coming to the detector so that the detector can measure the high intensity IR radiation. The detection range and ND filters are detailed in the following Section 2.5.

2.4 Calibration to find a linear conversion function

A thermal/photon count IR camera is designed to generate raw digital counts from each pixel in recorded image array. Then these digital count data are converted to radiometric units. This conversation can be done in the camera or in the software designed by the manufacturer of the camera. The camera output is formed based on an embedded mathematical formula which converts the raw digital count values into radiometric data (like temperature). This formula is usually obtained through calibration procedures. Since the detector and other electronics parts in cameras are generally designed in a way to work linearly, a linear conversion function is derived in the calibration procedures, transferring the camera input and output. The readout integrate circuit (IC) and the analogue to digital (A/D) converter of camera are also linear over a certain range of their performance. To make it simple, the goal of calibration steps is to find that the linear function that coverts input incident thermal radiation flux/photon count into temperature.

For example, if the digitizer of a MWIR thermal camera is a 14-bit unit, it can provide count values from 0 to 2^{14}-1 (which is 16383 steps). This means that A/D convertor in the camera can convert analogue voltages from detector into digital numbers in a range of 0 to 16383. If the maximum voltage (from maximum recorded temperature before saturation) of a detector is 10 volts, in ideal case, we expect to map that the voltage on a digital number/count equivalent to 16383. However, due to some other parameters, such as Non-uniformity Correction (NUC) required because of camera's own heat (see Section **Error! Reference source not found.** for more details), the maximum digital count with NUC would be approximately 14000. If we point the camera to an object, and we get the digital count number more than 14000, it means that the detector of the camera is saturated.

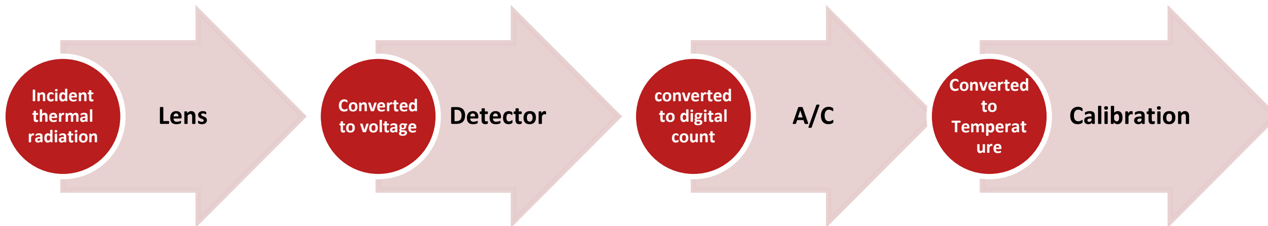


Figure 5. Consecutive essential steps in IR camera from incident radiation to temperature information.

2.5 Temperature Range/Span and Neutral Density (ND) filters

The detector of a thermal/photon count IR camera has a limit in the detection range. Outside the detection range, for radiation intensities higher or lower than the limit, the measurement reading will be saturated at the upper or lower limit of the detection range, respectively. In the saturated output regions, the detector cannot distinguish radiation details/intensities between each pixel.

The detection range of a camera is dependent on the amount of thermal radiation reaching to the detector sensor. In general, the detection range of a standard lens is relatively narrow, yet the range could be expanded by coupling with a filter. To expand the detection range to include elevated temperatures up to flame temperatures, we have to limit the amount of thermal radiation reaching to the detection. Neutral density (ND) filters are designed to have a constant transmission, based on the wavelength over the bandpass of the camera (i.e., FLIR company sells ND1, ND2, and ND3 versions, which have a transmission of 10%, 1%, and 0.1%, respectively). It is noteworthy to mention that limiting the radiation reaching to the detector with a ND filter will increase the detection/temperature range, yet with the cost of losing the thermal sensitivity/temperature resolution. At the same time, because of smaller view angle of the filter, we also lose part of the angle of view (FOV) for the camera.

For example, the standard detection range of a MWIR camera with InSb detector (e.g., FLIR A8303sc) provided by the manufacturer would be from -20 to 350°C. The standard detection range of a LWIR camera with SLS detector would be from -20 to 650°C. Using ND filters, the detection range could be expanded or changes. With one ND1 filter attached to a FLIR A8303sc with InSb detector, the temperature measurement range can be enhanced to be from 45°C to 600°C. With one ND2 filter, we can expect to see a temperature range of 250°C to 2000°C, and with one ND3 filter, the temperature range will be extended to be from 500°C to 3000°C. While the detector is the same, and the ND filters only change the transmission percentage of the IR radiation to the detector, the camera integration time should be tuned accordingly. Furthermore, using ND filter with a low transmission rate will lose detection of a lower range of the temperature and deteriorate the thermal resolution of the camera due to the fixed dynamic range of analogue to digital (A-to-D) converter in camera. Thus, recording images for elevated/wide temperature ranges with ND filters will cost losing lower temperatures and thermal sensitivity.

2.6 Integration Time

Integration time is a property of photon detector, referring to the time during which the photon counter/detector collects energy. Detailed explanation of this term is out of scope of this report. Briefly, during the integration time, the photons of IR signal striking the detector pixels are converted into electrons and stored in an integration capacitor (in detectors which work with capacitors as in MWIR cameras). The pixel is electronically shuttered by opening or shorting the integration capacitor for the integration time, which varies with the detection range. Figure 5 shows different integration times for various detection/temperature ranges used by the FLIR Company with SWIR and MWIR cameras. Typical integration times for -20°C to 350°C objects with a FLIR InSb camera generally range from about 6 ms to 50 µs depending on the camera model. These really short integration times make it possible to “stop motion” and accurately measure very fast thermal transients. Integration time is like the camera speed in RGB cameras. When integration time is small, camera can capture higher temperature range but with more noises, and vice versa.

When necessary to measure a wide temperature range, it is not possible to use only one integration time setting in imaging a wide temperature range with a high-resolution accuracy. In other words, we need to use multiple sub-ranges of temperature overlapping to cover the total temperature span, with each sub-range with a suitable integration time. To collect the data while simultaneously switching the multi integration times and the multi sub-ranges of temperature, we can use super-framing feature of FLIR MWIR cameras. Super-framing option of FLIR cameras can be repeatedly cycled through up to 4 integration time pre-sets (or temperature ranges), and the result image can be combined automatically to generate one long temperature range. However, this feature still cannot support the full temperature range over 350°C required in applications to fire environment.

In application to fire environment, a target range of temperature could be around 40°C to 1200°C, to cover from ignition to flaming, so measuring the wide temperature range would become more challenging since the elevated temperature range (e.g., greater than 350°C) is required to use a ND filter to limit the radiation reaching the detector. Thus, even with super-framing feature allowing multi sub-ranges of temperature, the measurement cannot cover the temperature range lower than 250°C, unless there is a physical mean in the camera to automatically place/remove the ND filter following the rapid super-frame cycle.

To record videos by a MWIR camera from fire scene with a wide temperature range, the only option we have is to conduct in-house calibration, and find a pre-set with one integration time which works accurately as much as possible to the target temperature range (e.g., 40°C to 1200°C).

LWIR SLS Camera, f/2.5 7.5-10.5 μm		
Int T (ms)	Temp Range (°C)	Filter
0.1600 ms	-20°C to 150°C	None
0.0410 ms	55°C to 350°C	None
0.0146 ms	150°C to 650°C	None
0.0718 ms	250°C to 1000°C	ND1
0.0280 ms	400°C to 2000°C	ND1

Table 1 – LWIR SLS Camera Performance Metrics

MWIR InSb Camera, f/2.5 3.0-5.0 μm		
Int T (ms)	Temp Range (°C)	Filter
2.0205 ms	-20°C to 55°C	None
0.8442 ms	10°C to 90°C	None
0.2403 ms	35°C to 150°C	None
0.1040 ms	80°C to 200°C	None
0.0179 ms	150°C to 350°C	None
0.3218 ms	250°C to 600°C	ND2
0.0535 ms	500°C to 1200°C	ND2
0.0191 ms	850°C to 2000°C	ND2

Table 2 – MWIR InSb Camera Performance Metrics

Figure 6. Integration times for LWIR and MWIR FLIR cameras.

2.7 Drift Temperature and Non-Uniformity Correction (NUC)

If the IR Camera is turned on and left running for several hours, the temperature of the optics and detector of the camera can change substantially due to the camera electronics power dissipation or even due to the weather condition. Also, as a thermal/photon count IR camera used in the field is usually subjected to heat sources, its optics and other components get warmer. For this reason, we need to correct this temperature difference by setting drift temperature (T_{Drift}). This parameter is particularly important in cases of measuring cold materials. On the other hand, for hot objects such as fire, an amount of drift temperature is usually negligible. This draft temperature is usually identified in the factory through testing using lots of blackbodies in controlled environments. Some cameras (e.g., FLIR A8303sc) allow users to set this temperature during user calibration to overwrite the default temperature set by the factory.

To compensate the drift temperature and correct the consequent measurement shifts caused by parasitic radiation gained from the environment, the parameter of Non-Uniformity Correction (NUC) is set. The NUC function is obtained through the calibration to correct a degree of intrinsic non-uniformity across pixels of the detector.

The NUC process is done in the camera unit or on the software that the camera is connected with to correct these non-uniformities. It is possible to create a user NUC file during in-house calibration, but it requires complicated calculations using lots of uniform black bodies being placed closely to a camera. This requirement is often not possible and safe for very hot temperatures. Thus, NUC files are usually created by the factory of the camera per each pre-set (i.e., integration time). In our calibration, we used the NUC files provided by the manufacture since the factory pre-set NUC file is generally valid for our application cases focusing on flame and smoke.

3 Calibration Set-up

In this section, we will briefly introduce devices and software we used for calibration of a FLIR MWIR A8303sc camera, which has the capability of user calibration. Calibration requires at least two calibrated blackbodies as reference heat sources, and software for recording data and generating calibration files. In our calibration, we also used other cameras and devices in parallel to compare the accuracy of each device and evaluate our calibration performance.

3.1 Camera

To undertake in-house calibration, the camera must have the capability of uploading and downloading calibration files to the memory of the camera with a specific software. In this report, we performed in-house calibration for a mid-wave IR photon counter camera (MWIR), FLIR A8303sc (see Figure 6). Based on the manual of FLIR A8000sc-Series, this type of camera works seamlessly with FLIR ResearchIR Max software, and it has the capability of overwriting factory calibration with user calibration files. Brief specifications of FLIR A8303sc relevant to this report are listed in Table 1**.**

Figure 7 – FLIR A8303sc MWIR camera used for in-house user calibration

Table 1 – Relevant specifications of FLIR A8303sc camera used in in-house calibration

Detector type	FLIR indium antimonide (InSb)
Spectral Range	3.0 – 5.0 µm
Resolution	1280 x 720
Sensor Cooling	Closed Cycle Linear
Minimum Integration Time	480 ns
Maximum Frame Rate	60 Hz

Dynamic Range	14-bit
Standard Temperature Range	-20°C to 350°C
Optional Temperature Range	Up to 1500°C Up to 3000°C
Camera f/Number	f/4.0
Available Lenses	17 mm, 25 mm, 50 mm, 100 mm, 200 mm
Focus	Manual
Filtering	Behind-the-lens filter holder

The IR camera (FLIR A8303sc) used in this calibration has an InSb detector with cooling refrigeration for the detection range of MWIR wave lengths. The focal lengths of lens available for this camera are variable from 17 mm to 200 mm (i.e., yet we have two lenses of 50 mm and 100 mm). We used 50 mm lens for the purpose of this in-house calibration. The 50 mm lens has the compatibility of attaching different filters with a filter holder, including ND and gas detection filters. Figure 7 shows the 50 mm standard lens and the ND2 filter used together.

3.2 Neutral Density (ND) Filters

As we discussed, the calibration of an IR camera means that we map digital count values of the input analogue to digital output (A-to-D) of temperature or radiance. Also, the digital mapping should be done with the detectable range since each detector has a minimum and maximum limit for detectable infrared radiation, and outside the range the detector reading becomes saturated and not accurate. The FLIR A8303sc camera with InSb detector (MWIR 3 to 5 µm) has the standard detection range from -20 to 350°C, calibrated by the manufacturer. The detectable range could be expanded by using neutral density (ND) filters, which have a constant transmission of IR radiation as a function of wavelength over the bandpass of the camera. We used a ND2 filter with a transmission of 1% to target the temperature range of 250°C to 2000°C.

We created 5 different calibrations with different temperature ranges. Here, we explained the one for a temperature span from 40°C to 1200°C as one individual calibration file. This is not a usual temperature range for ND2 filter, but we intentionally used that for monitoring fire growth from ignition to the suppression. Note that ND2 filter was attached to the lens of the camera during calibration and in each data recording the camera focused manually on blackbody surface and cavity.

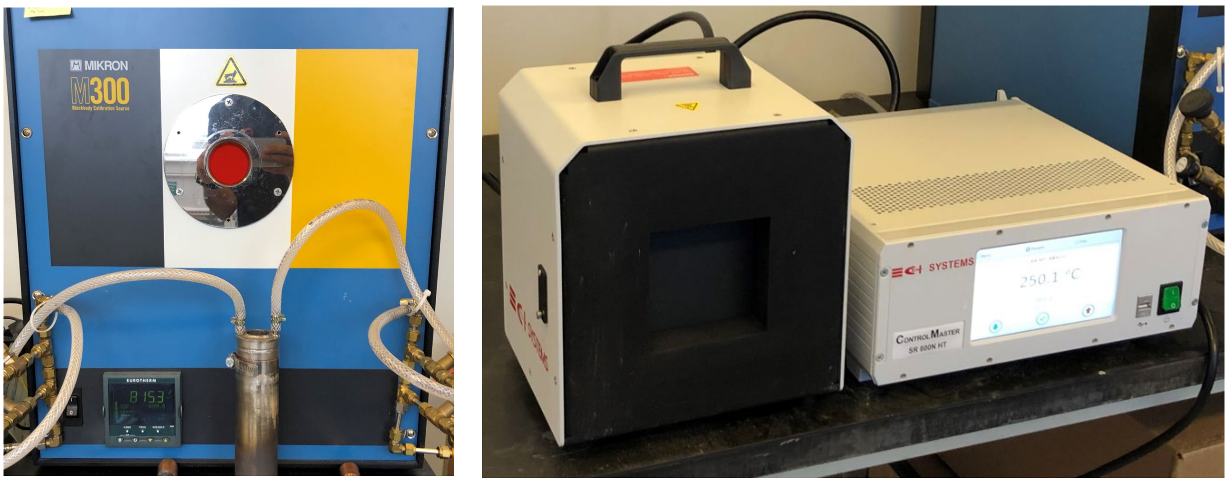
Figure 8 - FLIR 50mm f/4 HD lens for using with MWIR camera. On the right, ND2 filter attached on the back of Camera Lens.

3.3 Blackbodies

One difficulty for in-house calibration is that we need to have several blackbodies or at least one for the low/high ends of the temperature span, and another one for testing in the middle of the span. Heating up a cavity blackbody to 1200°C is often dangerous for the cavity and even for a camera in close proximity. To solve this problem, calibration is generally performed within the safe temperature range, and the obtained calibration data points are interpolated for elevated temperatures, often using a software (e.g., FLIR ResearchIR calibration software).

For accurate measurements, it is necessary to set a value of emissivity of a heat source in the camera settings. An emissivity value depends on the material of the source and the nature of its surface. Theoretically, the emissivity of one uniform object is the ratio of the energy radiated from the surface of various materials in the scene to that radiated from a perfect emitter of thermal radiation, called a blackbody. A blackbody is a physical device allowing uniform surface temperature control with the surface or cavity with great certainty of the emissivity of almost 1.0.

Figure 8 shows the two blackbodies used in our calibration: one with a surface (Ci-Systems, Control Master, SR 800N HT) and another with a cavity (Micron M300). As mentioned before, one specific feature of the blackbody device is that it has an emissivity of close to 1.0, and it perfectly absorbs and emits all thermal infrared radiation. Therefore, we expect negligible thermal reflection from a blackbody in a thermal IR camera.



(a) (b)

Figure 9 - Two blackbodies used in this report. (a) Cavity type blackbody (B) Surface type blackbody

3.4 Set-ups and comparison cameras

The experimental setup of our in-house calibration is shown in Figure 9 and Figure 10 for the cavity and the surface blackbodies, respectively. The surface or flat blackbody has the emissivity of 0.97 and the blackbody with a cavity has the emissivity of 0.99. Each temperature stabilized from several minutes to hours before recording and reading data.

The distance of A8303sc camera to the blackbody was measured, and the same distance was kept for all data point collections and recordings to be consistent between data points. To find the best distance, we first used FLIR A8303sc with its factory calibration pre-set without ND2+ filter for temperature of 200°C. At the distance of 0.7 m, the camera shows the temperature of the flat blackbody ROI (Region of Interest) as 200°C exactly. For this reason, 0.7 m was selected for the flat blackbody. For the cavity, we selected 0.7 m from the camera lens to the surface of the blackbody cavity as the fixed distance.

During the calibration, we check the temperature of blackbodies with other recently calibrated devices and compare with FLIR A8303sc camera. Specifically, we used:

- Dual Laser Video IR Thermometer
- FLIR IR camera T650sc
- FLIR IR camera K65

Figure 11 shows these devices with a corresponding sample output image for the surface blackbody with a temperature set on 600°C. Based on the distance to the blackbody and the time that blackbody was loading the temperature, each device shows 600°C with some errors which is acceptable range of ±2% (e.g., here it means ±12°C).

The FLIR T650sc camera, fixed behind the A8303sc, was approximately at 1 m from the blackbodies. Also, we recorded videos with the FLIR K65 camera and thermometer at approximately 0.7 m from the blackbodies for evaluation purposes. The A8303sc Camera was turned on for a half hour before the test, and it was kept on until the end of the calibration experiment. After the calibration process, we used the T650sc camera to see the temperature of the camera sensor and lens of FLIR A8303sc. The sensor was cool (around ambient temperature) in comparison to the lens (around 35°C).

Because we used the FLIR LWIR cameraT650sc in our comparison study and evaluation of calibration, few characteristics of this uncooled camera are highlighted here. The T650sc infrared camera offers thermal and visual imagery with a detector of 640 by 480 pixels and a temperature range of -40°C to 2000°C divvied into three subranges of -40 to 250°C, 100 to 650°C, and 200°C to 2000°C. The integrated thermal camera and 5.0-megapixel visual camera have matching FOV lenses that allow the correlation of targets over various distances with thermal and visible image overlays or MSX® (Multi-Spectral Dynamic Imaging) enhancement. The maximum radiometric resolution (dynamic range) of the camera is 14-bit, and the video recording has the maximum frame rate of 30 Hz. The spectral range of the camera is 7.5 to 13.0 μm. We used two FLIR T650sc cameras with the 24.6 mm of automatic and manual focused focal length lens in the evaluation section of our calibration performance.

Figure 10 - Different angles of Cavity blackbody use in the calibration process when FLIR A8303sc pointed to the cavity with temperature around 800°C.

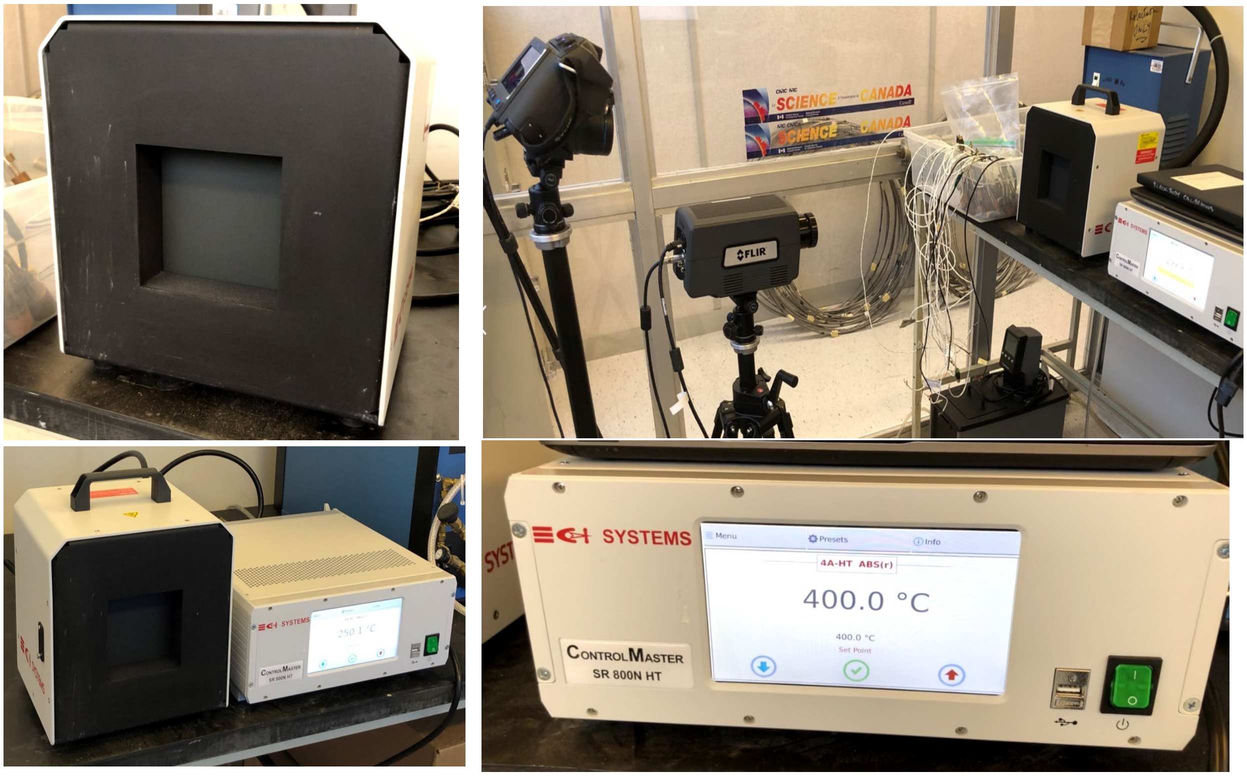
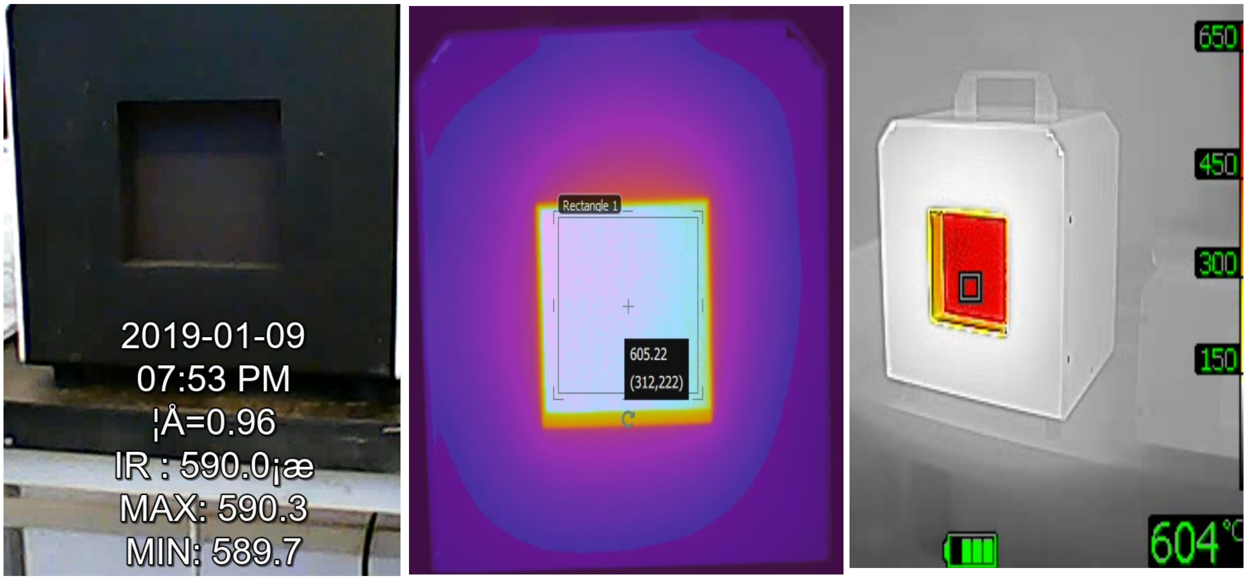


Figure 11 - Different angles of Flat blackbody use in the calibration process when FLIR A8303sc pointed to the cavity with temperature around 400°C.



(a) (b) (c)

Figure 12 – Other IR cameras used for verification of blackbody temperature and calibration progress of FLIR A8303sc. The figures also show the temperature reading of the surface blackbody with the temperature 600°C of (a) FLIR IR thermometer gun (b) FLIR T650sc (c) FLIR K65.

3.5 FLIR Research IR MAX

Software such as FLIR ResearchIR Max software or FLIR CalibratIR could be used in in-house calibration. The features of both software are almost the same, however, former one allows post editing of the temperature range.

Important note: Both ResearchIR and CalibratIR software do not allow user to enter data points with different emissivity. It means that for calibration, we can only use one type of blackbody, or blackbodies should have the same emissivity. For example, we cannot use two data points for 600°C captured from two different blackbodies with the different emissivities. We made several calibrations with different setups, however, to solve this issue of using one emissivity value, we used the surface blackbody for calibration and the cavity blackbody for testing.

Another important note is that both calibration software does not ask to enter integration time in calibration procedure, and we need to override the integration time during calibration based on the table provided by FLIR Company (see Figure 5). Steps of calibration procedure will be explained in the next section.

4 Calibration Procedure

In this report, one of our goals is to enumerate and explain steps to follow for in-house calibration of a FLIR MWIR A8303sc to ensure an acceptable measurement accuracy. The procedure can be generalized for other cameras if they have the feature to change integration time and upload calibration files into the camera. In order to evaluate our calibration results, the reading after calibration for different temperature were compared with that of other calibrated cameras and thermometers. Furthermore, we sent the in-house calibrated camera to the manufacture, FLIR company for factory calibration, and a comparison was made between our calibration (user) and the calibration made by FLIR company (factory).

4.1 Calibration Steps

Step one: As mentioned before, the calibration was done for a high temperature range using a standard 50 mm lens with a ND filter attached to the lens. It is recommended to clean the lens and filter appropriately before using (see). Also, when camera has ND filter, it is not possible to see low temperature objects, and for this reason, it is better to setup camera location and angle of view by a high temperature point of blackbody and then decrease temperatures in steps. Another important note is focusing on the blackbody surface or cavity. During each data point recording, we have to focus the lens as much as possible to reach more accurate calibration.

Figure 13 – ND2 filter cleaned and attached on the back of lens before calibration.

A camera and blackbodies are turned on and stabilized for recording data. In this step, an emissivity of and distance to a blackbody should be set in the camera. Our surface blackbody has an emissivity of 0.97, and cavity one has an emissivity of 0.99. Other parameters such as reflection temperature are negligible for temperatures more than 200°C, for this reason, we ignored that parameter by setting its default value. For lower temperature or other settings, this parameter should be re-calculated and set in the camera in advance.

Step two: Open FLIR ResearchIR MAX or FLIR CalibratIR in admin right mode for calibration (see Figure 13). Here, we used ResearchIR Max for recording videos of each data point (different temperatures of blackbody), and then we used CalibratIR software for creating calibration files. There are several options for creating user calibration with ResearchIR MAX and CalibratIR software from beginner to expert (see Figure 14). In the beginner mode, we point the camera toward the blackbody and only write temperature value in calibration wizard. After adding several data points with different temperatures, it is possible to save calibration files. The drawback of this method is that if something unforeseeable happens during the calibration procedure, we must perform the calibration from scratch. Another problem is that it does not allow editing data points and other parameters, such as low and high points of the temperature span (i.e., for this, the expert mode should be used for calibration). Using ResearchIR Max, we recorded an output file (*.seq) for each data point (see Figure 15), then add all points manually into the CalibratIR software. Note that entered was the average count value (average temperature of the blackbody surface or cavity) from each out file. The ResearchIR software has a filter called average frames which can used in finding the average value of 16 frames (after selecting one ROI).

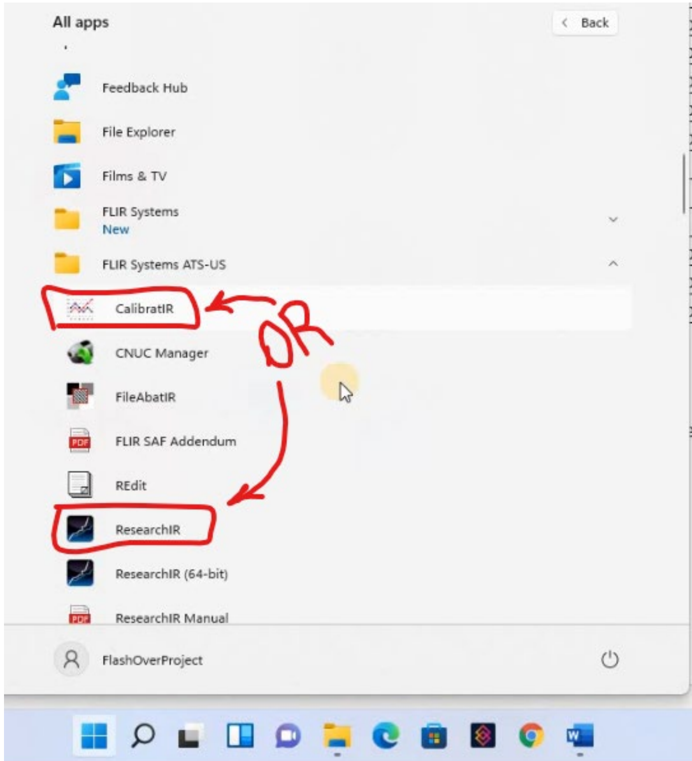


Figure 14 – We can do in-house calibration with CalibratIR or ResearchIR Max software.

Note: There are two output formats that we can use for the calibration: *.ats and *. sfmov. The difference between the two is that *. sfmov provides two or three separate data files as the output of the calibration process, which are modifiable for later analysis. For the current calibration, we used the *.ats format which provides only one file (i.e., a new FLIR software named FLIR Research Studio reads*.ats as a default format for data/video recording). To select the output format in ResearchIR Max, go to Edit → Preferences → Check or Uncheck the “Write ATS files instead of SFMOV/SEQ when possible”. We kept the ats format which is the default option.

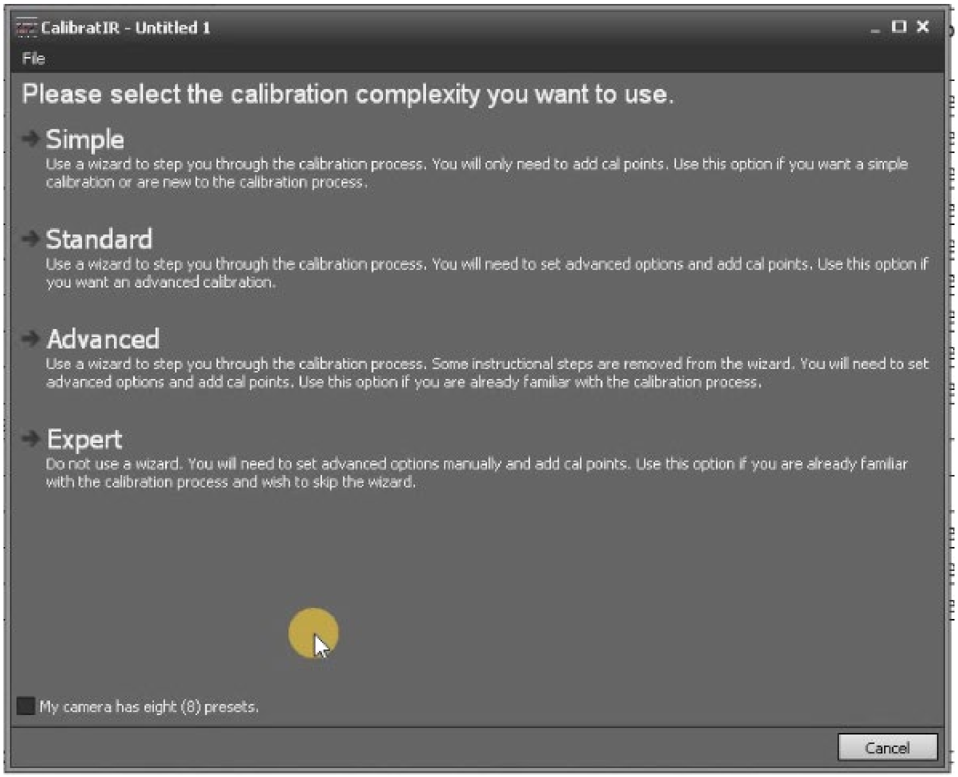
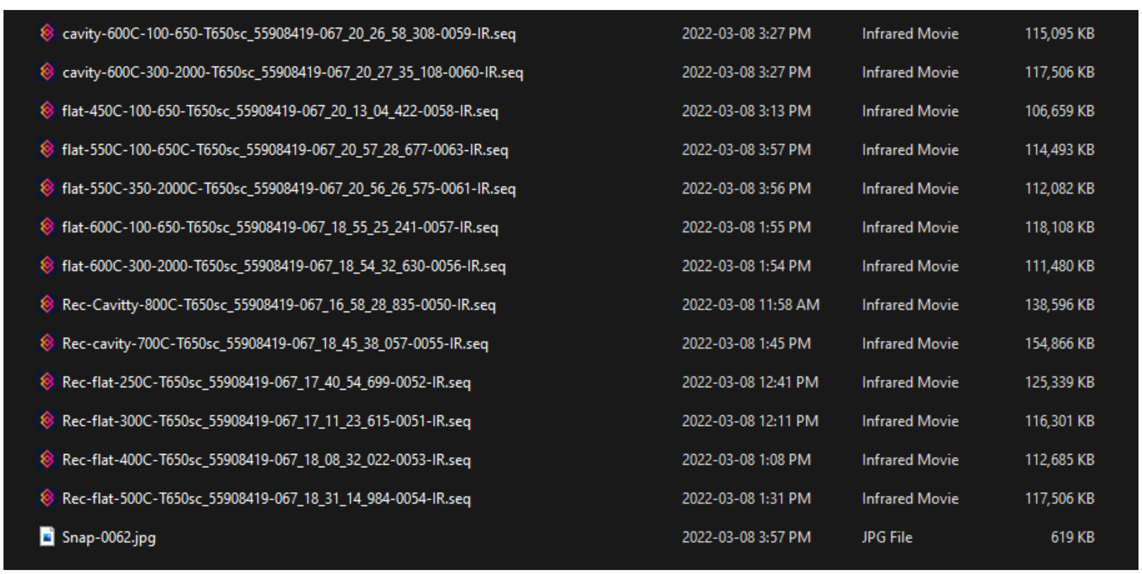


Figure 15 – First page that CalibratIR software shows to users



cavity-600C-100-650-T650sc_55908419-067_20_26_58_308-0059-IR.seq	2022-03-08 3:27 PM	Infrared Movie	115,095 KB
cavity-600C-300-2000-T650sc_55908419-067_20_27_35_108-0060-IR.seq	2022-03-08 3:27 PM	Infrared Movie	117,506 KB
flat-450C-100-650-T650sc_55908419-067_20_13_04_422-0058-IR.seq	2022-03-08 3:13 PM	Infrared Movie	106,659 KB
flat-550C-100-650C-T650sc_55908419-067_20_57_28_677-0063-IR.seq	2022-03-08 3:57 PM	Infrared Movie	114,493 KB
flat-550C-350-2000C-T650sc_55908419-067_20_56_26_575-0061-IR.seq	2022-03-08 3:56 PM	Infrared Movie	112,082 KB
flat-600C-100-650-T650sc_55908419-067_18_55_25_241-0057-IR.seq	2022-03-08 1:55 PM	Infrared Movie	118,108 KB
flat-600C-300-2000-T650sc_55908419-067_18_54_32_630-0056-IR.seq	2022-03-08 1:54 PM	Infrared Movie	111,480 KB
Rec-Cavitty-800C-T650sc_55908419-067_16_58_28_835-0050-IR.seq	2022-03-08 11:58 AM	Infrared Movie	138,596 KB
Rec-cavity-700C-T650sc_55908419-067_18_45_38_057-0055-IR.seq	2022-03-08 1:45 PM	Infrared Movie	154,866 KB
Rec-flat-250C-T650sc_55908419-067_17_40_54_699-0052-IR.seq	2022-03-08 12:41 PM	Infrared Movie	125,339 KB
Rec-flat-300C-T650sc_55908419-067_17_11_23_615-0051-IR.seq	2022-03-08 12:11 PM	Infrared Movie	116,301 KB
Rec-flat-400C-T650sc_55908419-067_18_08_32_022-0053-IR.seq	2022-03-08 1:08 PM	Infrared Movie	112,685 KB
Rec-flat-500C-T650sc_55908419-067_18_31_14_984-0054-IR.seq	2022-03-08 1:31 PM	Infrared Movie	117,506 KB
Snap-0062.jpg	2022-03-08 3:57 PM	JPG File	619 KB

Figure 16 – Recorded videos each for one temperature point of blackbody

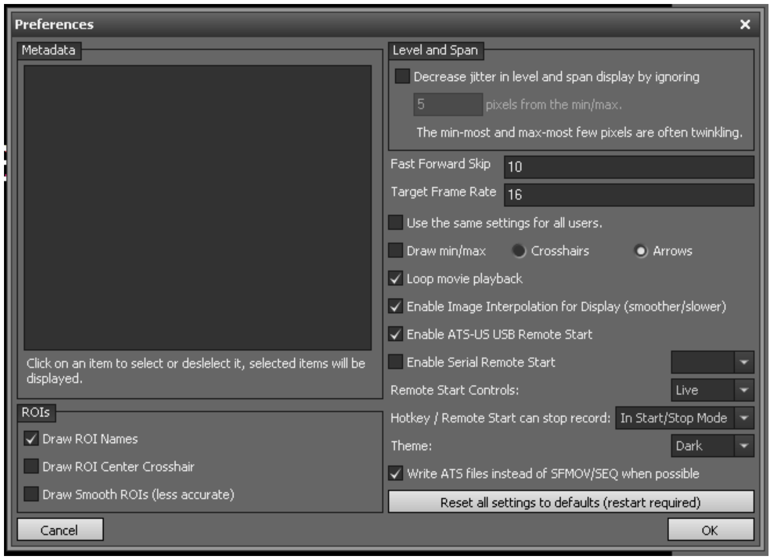


Figure 17 – ResearchIR Max can record videos in different formats.

Step 3: Till this step, the camera should be fixed at a specific distance from the blackbody and focused on the hot surface of the blackbody. The blackbody temperature should be stabilized, which might take several minutes or hours depending on the temperature. To override parameters of the camera, open the camera control from the menu of ResearchIR Max. A FLIR A8303sc camera has the control menu as shown in Figure 17. FLIR A8303sc has options of four different pre-sets with different integration times. However, during in-house calibration, we can use only one pre-set for recoding data points for calibration purposes. Integration times should be selected accordingly to the ND filter specifications. For our experiment, we set 0.3218 ms which was recommended by FLIR Company. For other three pre-sets, we should select no-factory calibration option in drop-down menu of integration time available in Figure 17.

Note: While integration time can be found from the FLIR Company data sheets based on filter and temperature range, an user can also find it through a trial and error process. By increasing and decreasing the temperature of blackbody and integration times, the best integration time for the temperature range could be found. However, this process is time consuming and laborious in practise. For this reason, the best option is to use the factory recommended integration times.

Note: to make sure that we have no user calibration available in camera, we need to clear the memory of ResearchIR if there is any prior user calibration. For this aim, we can select clear from user calibration menu in ResearchIR Max software (see Figure 18).

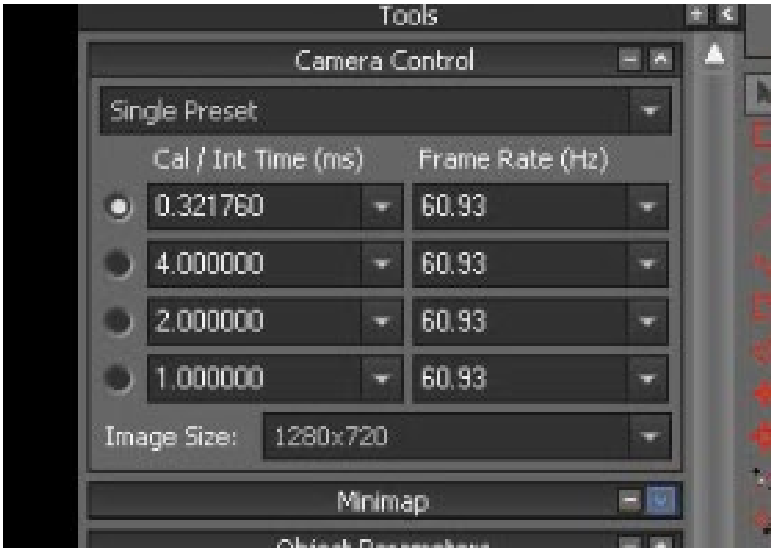


Figure 18 – Camera control menu of FLIR A8303sc in ResearchIR Max software.

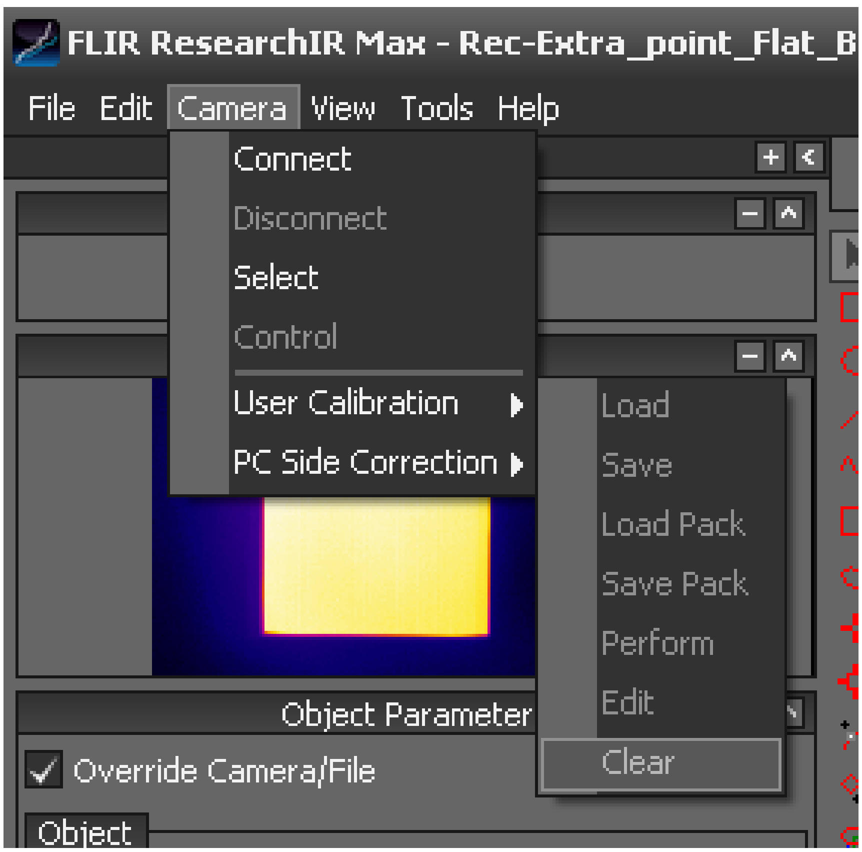


Figure 19 – Before recording data points we need to make sure we have no user calibration uploaded before.

If everything goes well, we should see 'count' on upper right side of the ResearchIR Max. Figure 19 shows the details of a typical recording and calculation step for one data point. As can be seen from the figure, we added a statistical analyzer and oscilloscope as well as one average filter on the ROI that was manually drawn for the hot surface of the blackbody (the yellow colour area). The oscilloscope should show consistent uniform counts. Otherwise, the ROI should be re-defined to get counts as uniform as possible. On the left side, we must override camera settings accordingly. Then, record a short video and write the average count value in a table.

Note: As mentioned in Chapter 2.7, to correct measurement shifts and the consequent non-uniformity across pixels, we need to use NUC files. NUC files can be from the factory or defined by a user. It is difficult for a user to create a NUC file for elevated temperature range. The reason is that we need to put the camera close to that elevated temperature, which is dangerous for the camera, and a user NUC file should be uploaded on the camera which delete the original factory NUC files on the camera. In this calibration process, we utilized the original NUC file from the factory designed for lower ranges of temperature. There are other corrections such as reflection and drift temperature which are negligible for temperatures greater than 200°C. Spatial calibration is also not important for our test. For each step of temperature setting on the blackbody, we also recorded short videos by FLIR K65, FLIR T650sc, and FLIR Thermometer. These data were used for evaluation of the calibration results (see Chapter 5).

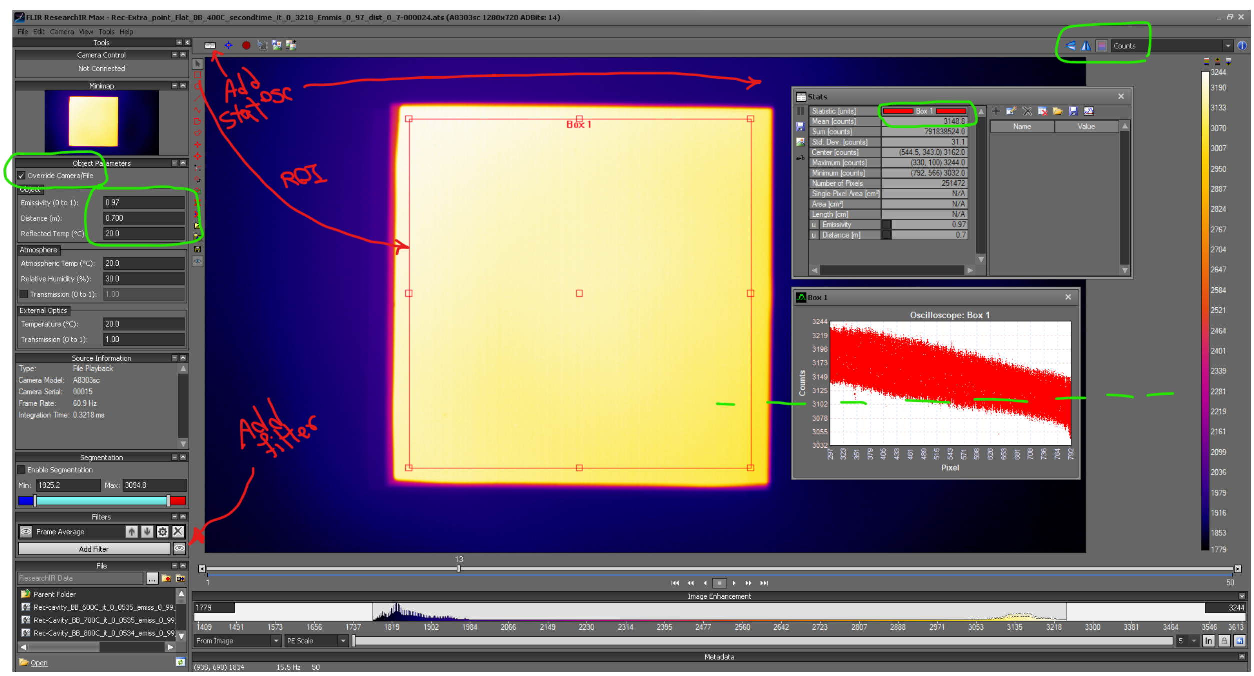


Figure 20 – A recording window (blackbody surface temperature was set on 400°C)

Important Note: if the count value is high as 13000 for low temperature ranges, the integration time requires to be corrected. With the correct integration time, we can expect to see a count value around 6000, when the maximum capability of the camera detector was set for 600°C using ND2 filter.

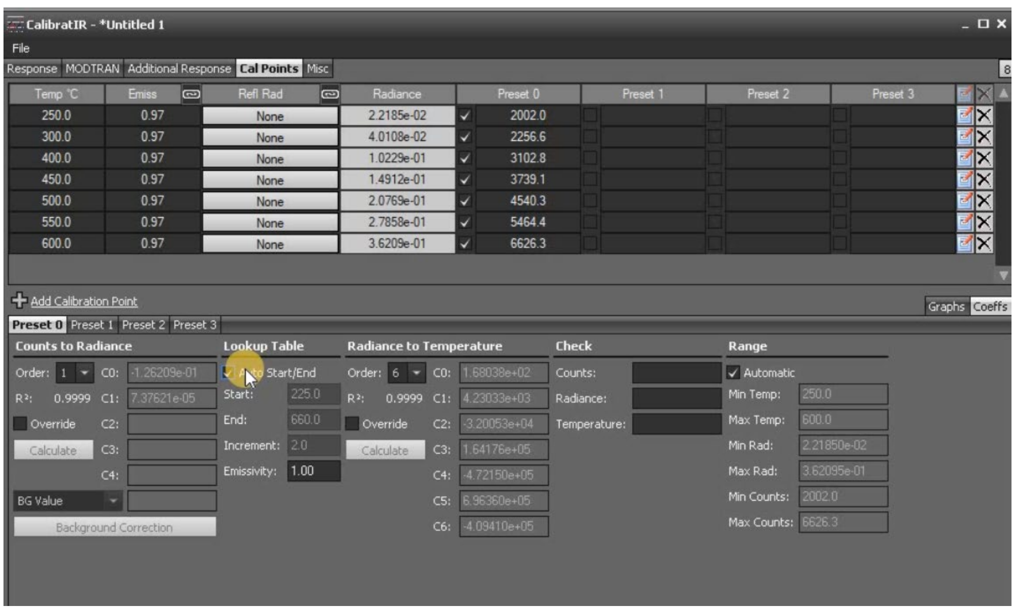
Important note: We are calibrating FLIR A8303sc for temperature range from 40 to 1200°C. As we discussed, generally for factory calibration files, the temperature range is separated into several parts with a different integration time for each. In user calibration, however, we can use only one integration time. Thus, we made calibration files having subranges, using two blackbodies. From many trials and errors, the integration time of 0.3218 was selected to cover temperatures from 50°C to 600°C. Table 2 shows the count value for each temperature step. With the integration time of 0.3218 for ND2 filter, the count value for the maximum temperature of 600°C is around 6000. It should be noted that because the A8303sc camera has 14-bit or 14000 count in digital to analogue converter, we can expect the camera to also provide correct temperatures greater than 600°C. Thus, for the elevated temperature range up to 1200°C, the calibration results were interpolated using CalibratIR software.

Table 2 – Data point recorded using two blackbodies and in different days.

With ND2 and Flat Blackbody					
Temperature value	Count value	Emissivity	Integration Time	Distance	Record
250	2002	0.97	0.3218 ms	0.7 m	done
300	2256.6	0.97	0.3218 ms	0.7 m	done
400	3102.8	0.97	0.3218 ms	0.7 m	done
450	3739.1	0.97	0.3218 ms	0.7 m	done
500	4540.3	0.97	0.3218 ms	0.7 m	done
550	5464.4	0.97	0.3218 ms	0.7 m	done
600	6626.3	0.97	0.3218 ms	0.7 m	done
With ND2 and Flat Blackbody					
Temperature value	Count value	Emissivity	Integration Time	Distance	Record
50	1721.4	0.97	0.3218 ms	0.7 m	done
100	1741.0	0.97	0.3218 ms	0.7 m	done
150	1785.0	0.97	0.3218 ms	0.7 m	done
200	1877.9	0.97	0.3218 ms	0.7 m	done
250	2040.0	0.97	0.3218 ms	0.7 m	done
300	2291.4	0.97	0.3218 ms	0.7 m	done
400	3147.5	0.97	0.3218 ms	0.7 m	done
450	3783.5	0.97	0.3218ms	0.7m	done
500	4573.9	0.97	0.3218ms	0.7m	done
550	5525.4	0.97	0.3218ms	0.7m	done
600	6633.2	0.97	0.3218ms	0.7m	done
250	2002.0	0.97	0.3218ms	0.7m	done
300	2256.6	0.97	0.3218ms	0.7m	done
400	3102.8	0.97	0.3218ms	0.7m	done
450	3739.1	0.97	0.3218ms	0.7m	done
500	4540.3	0.97	0.3218ms	0.7m	done
550-1	5464.4	0.97	0.3218ms	0.7m	done
600-1	6626.3	0.97	0.3218ms	0.7m	done

550-2	2154.2	0.97	0.0535ms	0.7m	done
600-2	2347.9	0.97	0.0535ms	0.7m	done
With ND2 and Cavity Blackbody					
600	2359.0	0.99	0.0535ms	0.7m	done
700	2833.7	0.99	0.0535ms	0.7m	done
800	3404.7	0.99	0.0535ms	0.7m	done

Step 4: After recording each data point as listed in Table 2, we need to open CalibratIR software. In the first window (see Figure 14), select Expert mode. Figure 20 shows few calibration points added to CalibratIR software. As can be seen from the figure, we have to set start and end point of calibration files manually. The CalibratIR provides a visualization of linear line fitted on data points. Measured and curve fit should be overlapped as possible.



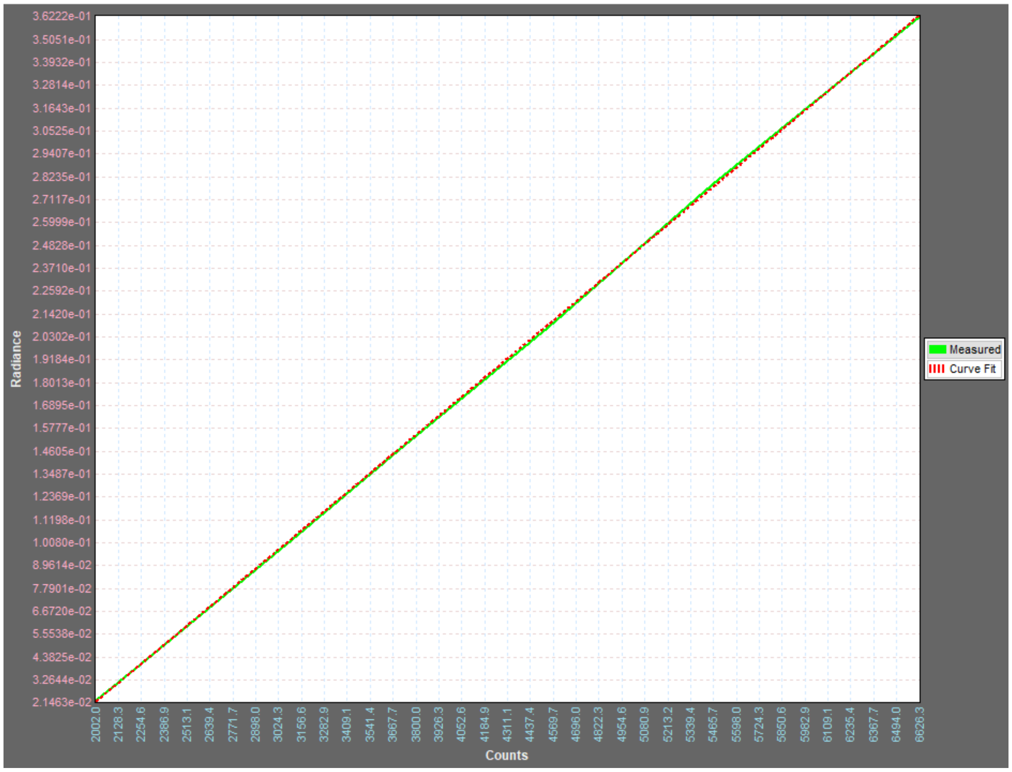


Figure 21 – Calibration points are being added to the CalibratIR software.

Note that all these steps are possible with the assumption of linearity for all components of the camera. When we add all data points to the software, set start and end points, and see a linear curve which is near to the measured curve. Then, we can save calibration files. Calibration files should have two formats of *.cal and *.inc in one folder.

Step 5: Now we have calibration files available, it is recommended to test the calibration files outside the data points, for the temperatures which we didn't have in the calibration. To make sure that our calibration is good, it is also better to use another blackbody for testing.

4.2 Quick checks with blackbodies

We created a calibration file for the FLIR MWIR camera A8303sc. In general, calibration folders should have enough information about the calibration settings and files at least two formats (*.CAL and *. Inc) (see Figure 21).

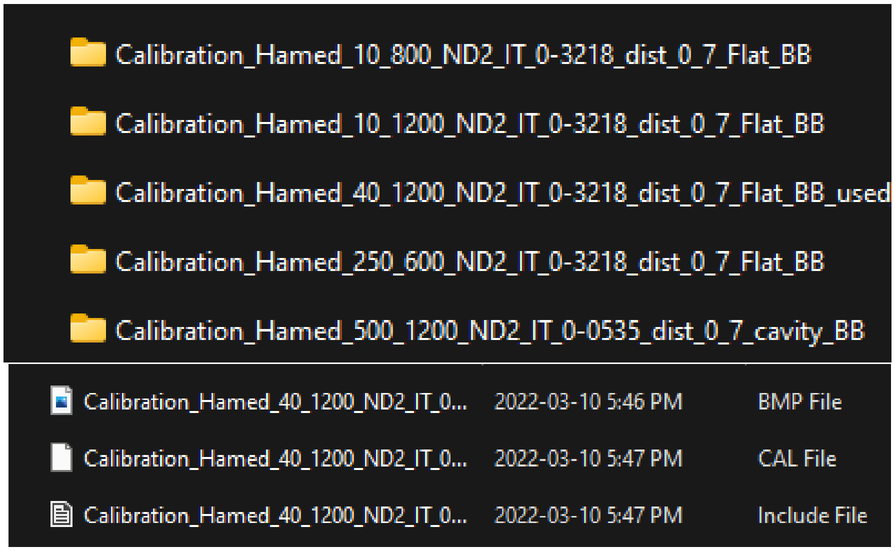


Figure 22 – Calibration results saved by CalibratIR software.

To test our calibration performance over the temperature range of 40°C to 2000°C, we first upload the calibration file on ResearchIR MAX software when the camera is connected to the software. Figure 18 shows the menu that we should use to upload our user calibration files to the software. Note that we need to override the settings of the camera after loading user calibration such as integration time, emissivity, and distance. We placed the camera in front of our blackbody with cavity for testing. The blackbody temperature was set on 700°C and stabilized for several hours (see Figure 22). Also, we did the same test for surface blackbody when its temperature was set to 370°C (see Figure 23). Using our user calibration, the FLIR A8303sc shows the average temperature of blackbody cavity as ~708°C and blackbody surface as ~377°C. If we consider 2% error for each test, our calibration works below that error threshold. Note that blackbodies also have errors which we need to consider. The FLIR T650 for the blackbody with cavity set for temperature of 700°C shows temperature of ~716°C (Figure 24) while FLIR thermometer for the same blackbody shows ~710°C (see Figure 25). In the factory calibration (see Appendix A, page 5), the tolerance for the temperature 700°C is ±14.00°C and for 350°C in lower range is ±7.00°C. Comparing with the factory calibration report, our calibration is within the tolerance of FLIR calibration standards.

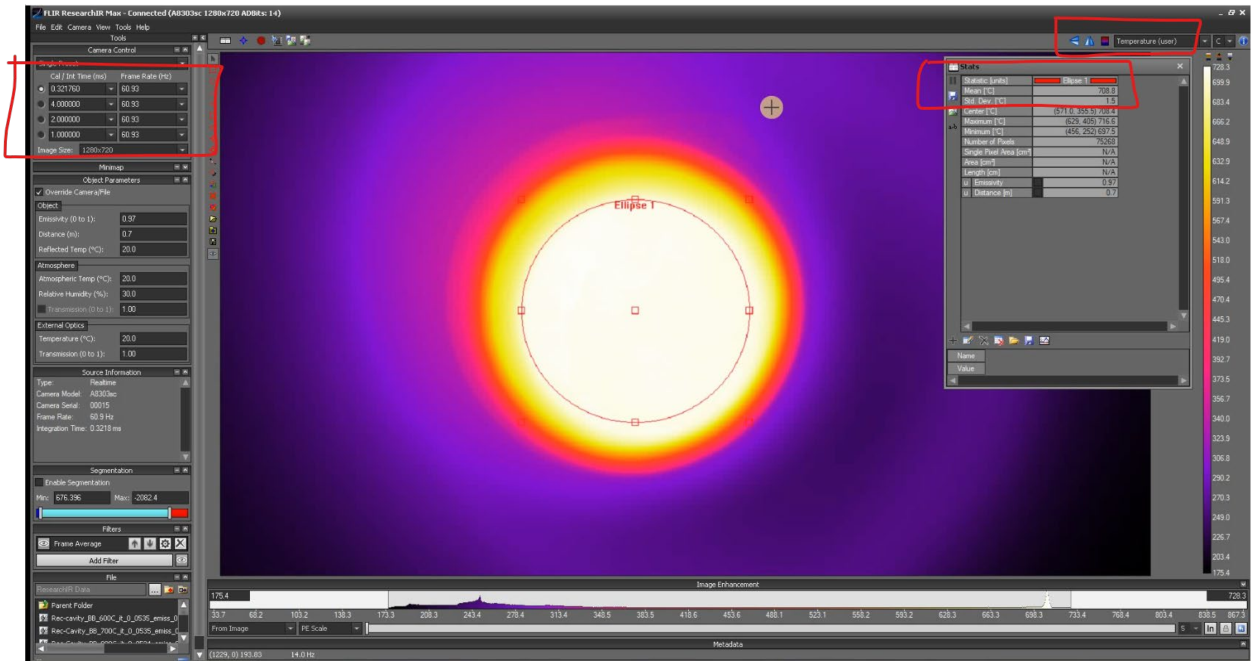


Figure 23 – Temperature reading of blackbody with cavity set on 700°C, after loading user calibration for temperature from 40°C to 1200°C.

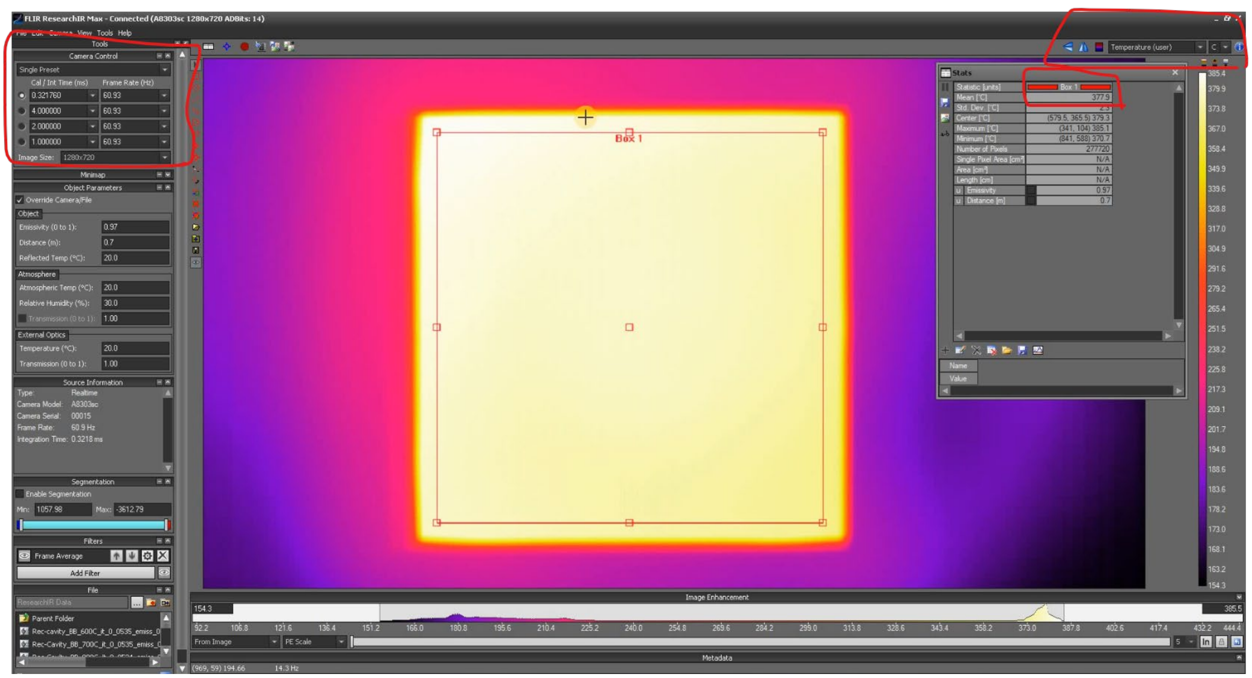


Figure 24 – Temperature reading of blackbody with surface set on 370°C, after loading user calibration for temperature from 40°C to 1200°C.

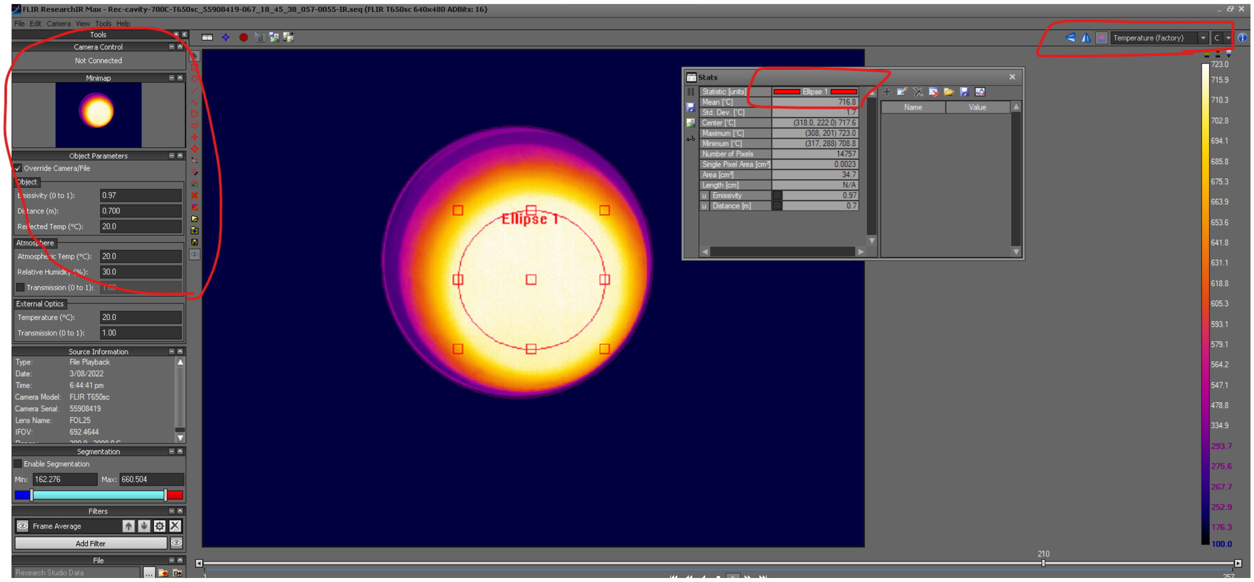


Figure 25 – FLIR T650 camera temperature reading of blackbody with cavity set on 700°C, after loading factory calibration for the range of 300°C - 2000°C

Figure 26 – IR thermometer temperature reading of blackbody with cavity set on 700°C

5 Calibration Evaluation for Real Fire Tests

This section shows the evaluation of our user calibration conducted using the ND2 filter for the range of 40°C to 1200°C, which is not a common temperature range of this camera. In our calibration, an integration time was chosen to accurately accommodate the wide temperature range. The user calibration covering the wide temperature range enables to collect temperature data of a fire without using the super-framing feature of the camera, which is also limited in covering the wide temperature range.

The evaluation of our calibration was conducted by running full-scale room fire tests. A wood crib fire was set in a test room with the dimensions of 3.6 m (W) X 2.4 m (L) X 2.4 m (H). Figure 26 illustrates the room fire test set-ups. The FLIR MWIR A8303sc camera was configured to use our in-house calibration and placed to aim the wood crib fire. To evaluate the temperature readings of the A8303sc camera, we installed thermocouples at different heights of 0.8 m, 1.6 m and 2.4 m, right at the center of the wood crib fire (i.e., in Test #5, #6, and #7). The MWIR camera and other IR and vision cameras were placed outside of the room in the distance of around 10 m from the opening area. Figure 27 shows actual experimental set-up of our tests and all image-based devices utilized in these experiments, including FLIR A8303sc, two FLIR T650sc with setting of temperature range up to 650°C and up to 2000°C, FLIR K65 Firefighting thermal imager, FLIR One Pro, FLIR Thermometer Gun, and two vision-based RGB cameras. For all experiments, we used emissivity of 0.92. The readings from the user calibrated FLIR A8303sc was compared with those from other imaged based devices.

For a direct comparison with the thermocouple data at 0.8 m, 1.6 m and 2.4 m, the temperature data from FLIR A8303sc and FLIR T650sc were extracted at the same measurements points. Because of the view orientation and the different opening size used in each tests, the data extraction were done with the heights of 1.6 m and 2.4 m. For this data extraction, we used FLIR Research Studio Software which has the ability to calculate average temporal temperature data over a region of interest. Figure 28 and Figure 29 illustrate examples of temporal temperature data extraction from IR videos over the thermocouple locations. Note that for the temperature data comparison, we first time-synced all IR camera data and the thermocouple data.

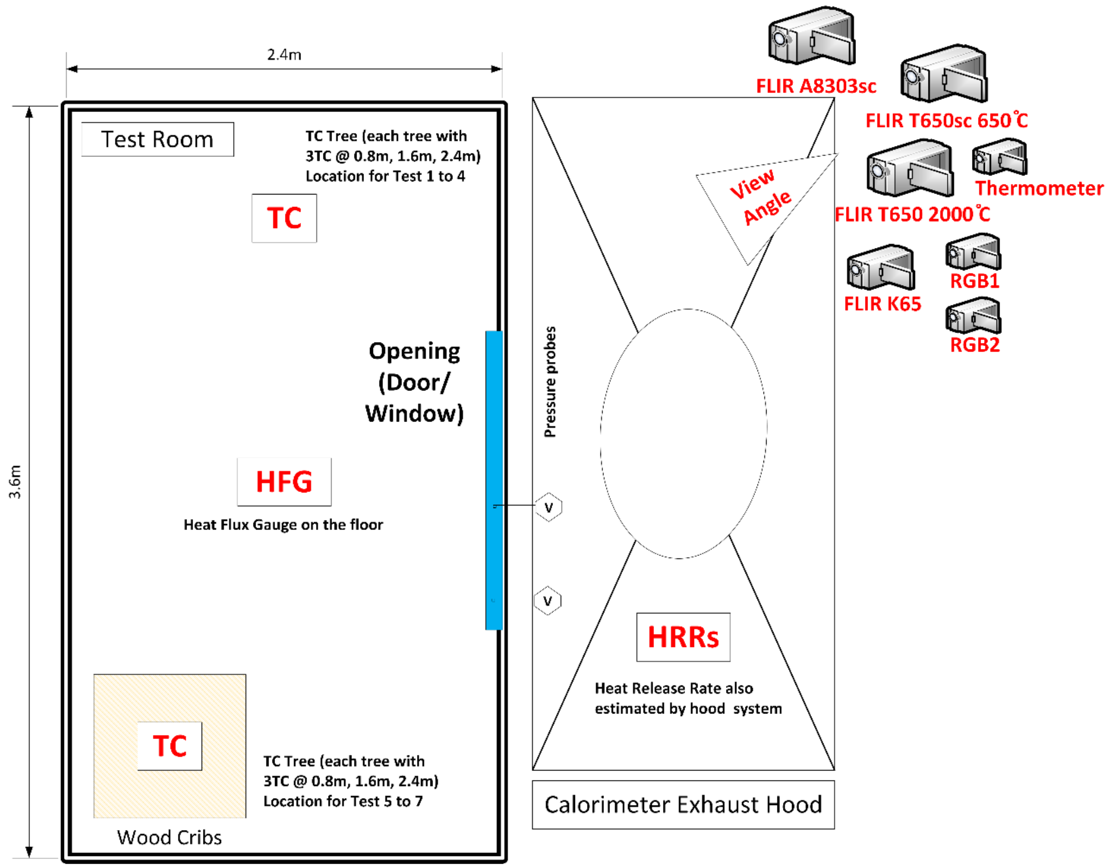


Figure 27 – Schematic of room fire test and location of cameras and TC trees. Note that TC tree is located inside the wood cribs for three tests (used in this report). Detailed location of cameras can be seen in Figure 27.

Figure 28 – A: Opening area in one of room fire tests with flashover occurrence, B: thermocouple tree, C: distance of camera to the opening and hood location above it, D: a general view of all imaging devices used in room fire tests.

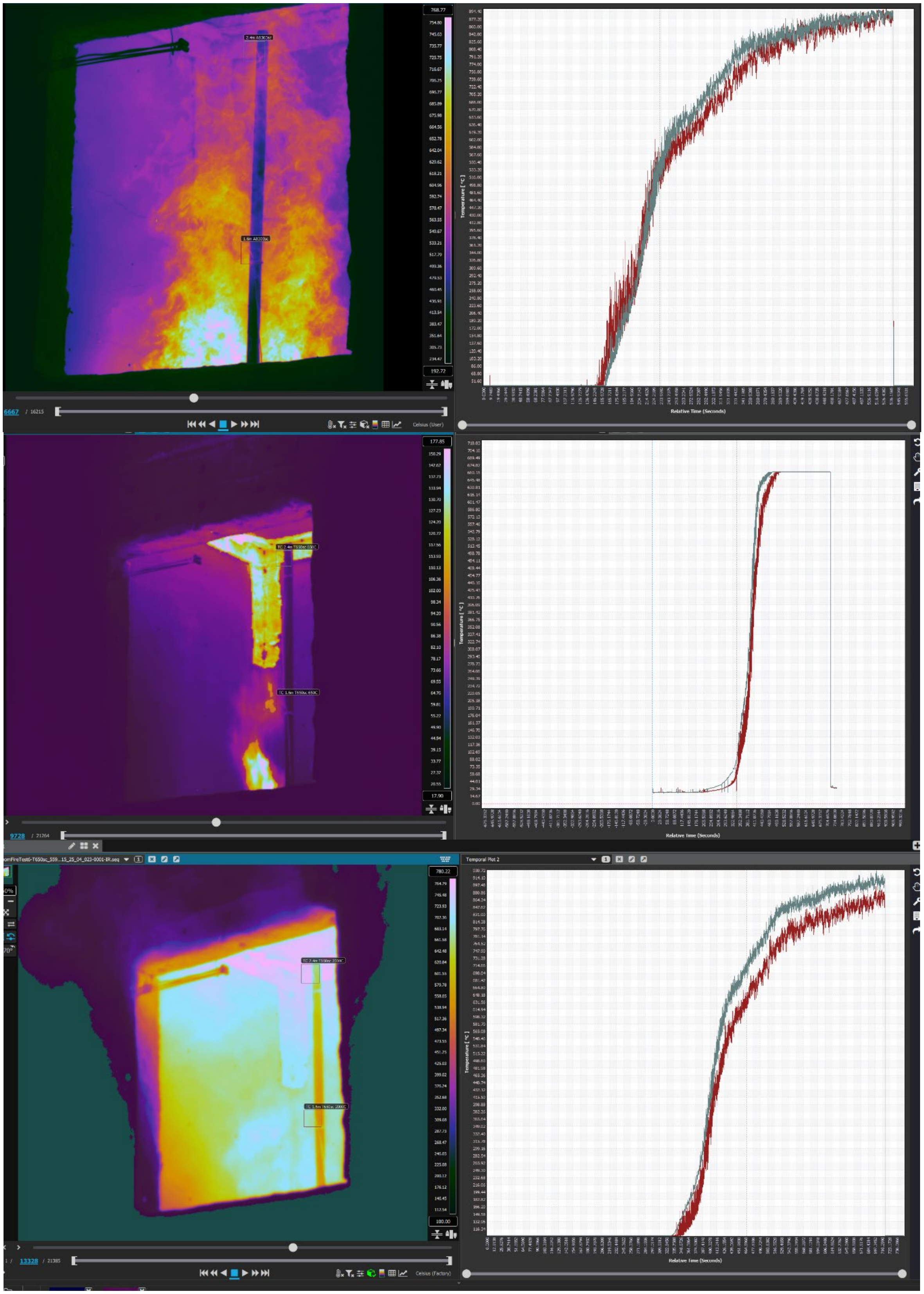
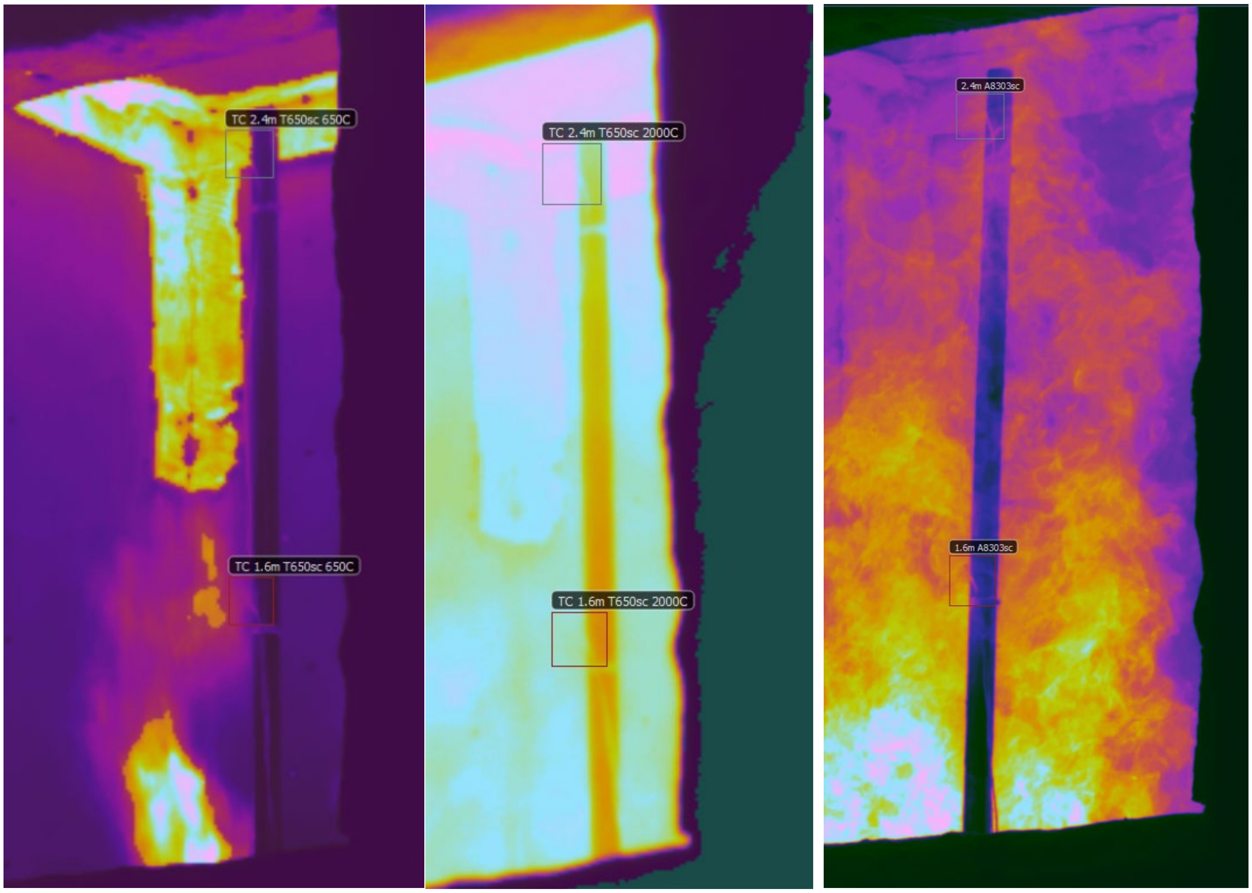


Figure 29- Examples of extracting temporal temperature data from IR camera data.



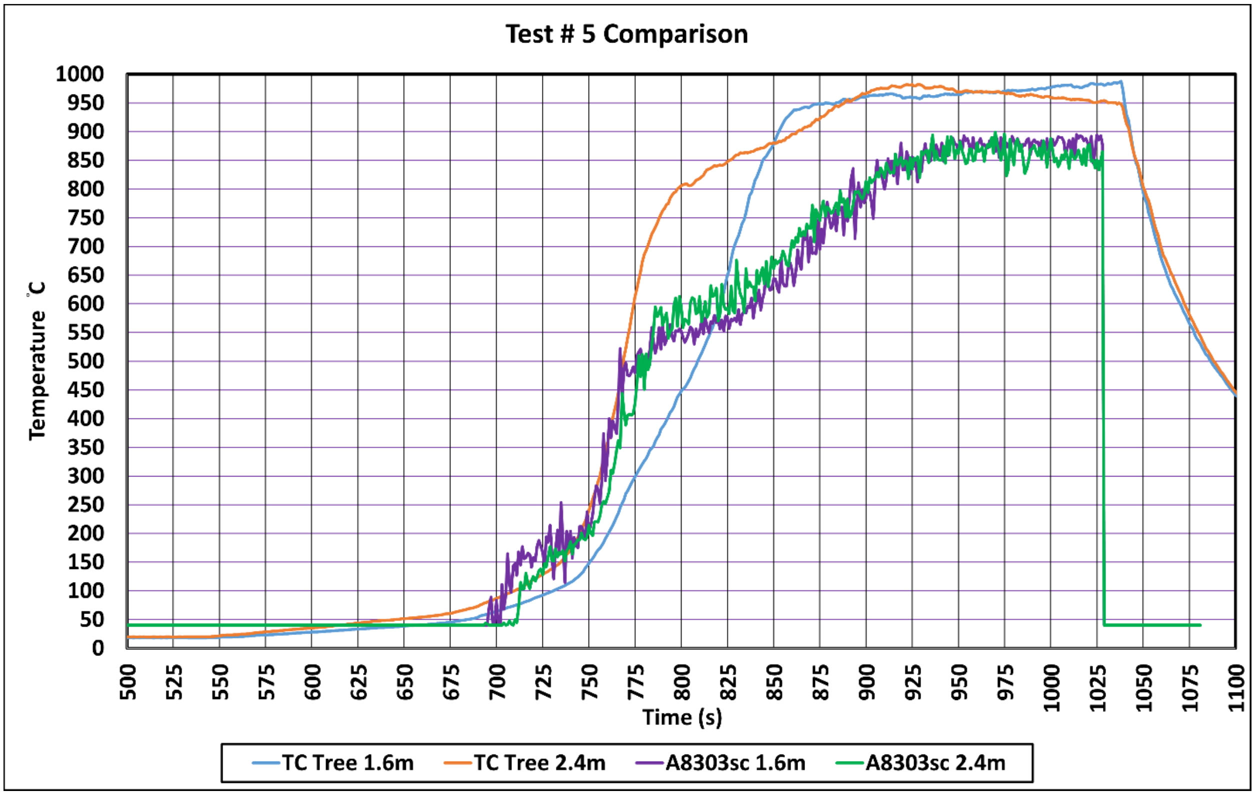
FLIR T650sc up to 650°C FLIR T650sc up to 2000°C FLIR A8303sc up to 1200°C

Figure 30- Zoomed version of Figure 28 over thermocouple tree in 1.6 m and 2.4 m heights.

5.1 Comparison of FLIR MWIR Camera A8303sc with thermocouples

After the time synchronization of all image data, we compared the temperature data extracted from the data acquired by the FLIR A8303sc camera with the temperature data recorded by the thermocouples placed in the wood crib fire. Figure 30 compares the results of two tests (i.e., test #5 and test #6) for the temperature at height of 1.6 m and 2.4 m.

Since the MWIR camera was calibrated for the range of 40°C to 1200°C, the camera was insensitive to the small temperature changes at the time of ignition. However, above the low end temperature of 40°C, the readings of the MWIR camera showed comparable results to the thermocouple data. Both devices had almost the same temperature trends for a temperature range up to 550°C. After the fire became fully developed, the temperature readings from the MWIR camera appeared lower than the thermocouple data. This discrepancy was attributed to the difficulty in extracting flame temperature data from the MWIR camera, which was obstructed by the metal bar of the thermocouple trees. Also, it should be noted that thick smoke was built up in the upper part of the test room when the fire was fully developed, thus, the thick smoke layer lowered the transmittance of the radiant heat since smoke is the principal absorber of radiance in the combustion environment including the waveband of the MWIR camera (i.e., 3.0 – 5.0 μm).



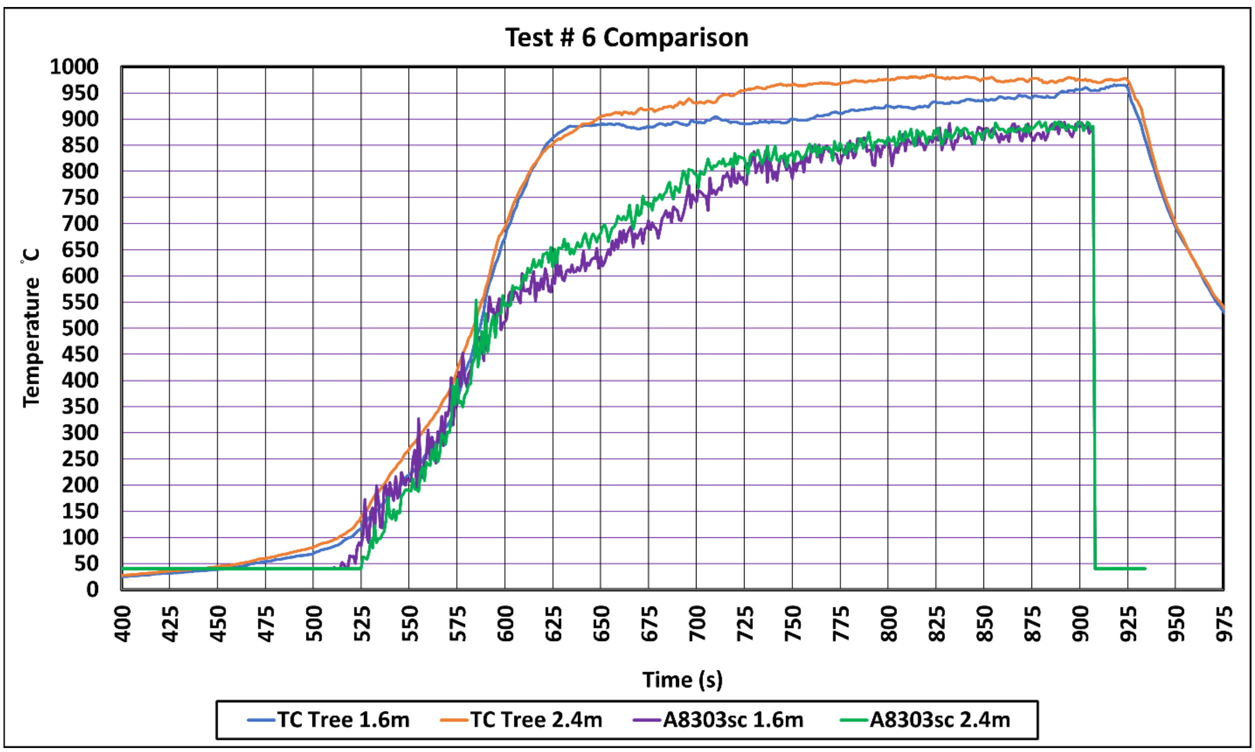


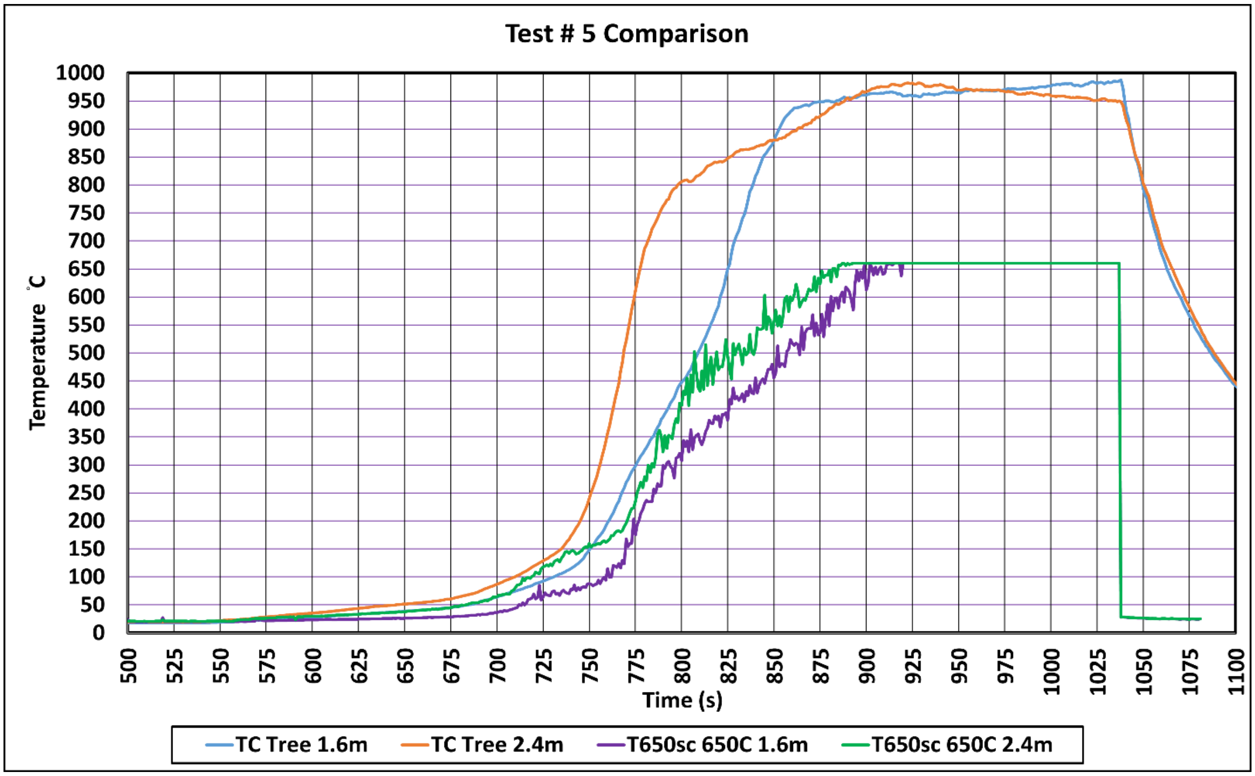
Figure 31 – Comparison of temperature data extracted from video recorded by FLIR MWIR A8303c camera with temperature data recorded by thermocouples installed at 1.6 m and 2.4 m height in two separate actual room fire tests.

5.2 Comparison of FLIR LWIR Camera T650sc with thermocouples

Figure 31 and Figure 32 show a comparison of the temperature trends extracted from the two LWIR T650sc cameras with those recorded by the thermocouples used in the two room fire tests. Note that T650sc cameras have three calibration settings, and we used two separate temperature ranges: 100°C to 650°C for one T650sc and 300°C to 2000°C for the other T650sc. It should be noted that the spectral range of the T650sc camera is 7.5 to 13.0 μm, which is known to show lower thermal resolution than the MWIR band of 3 to 5 μm in the elevated temperature region.

Due to the temperature range setting, one of the T650sc cameras experienced saturation around 650°C (see Figure 31) with a flat curve. On the other hand, the other T650sc camera with the temperature span 300°C to 2000°C showed the reading comparable to the thermocouple data. However, it was also observed that the readings very near the low and high ends of the detection/temperature range have the relatively low accuracy.

From this comparison, we can see that the factory calibrated two temperature spans of T650sc camera are complementary of each other, and we can combine them similarly to the super-framing feature to generate output data with a larger temperature span to cover from the ignition to fully developed fire. This could be a promising future feature, which can be added to uncooled cameras such as T650sc.



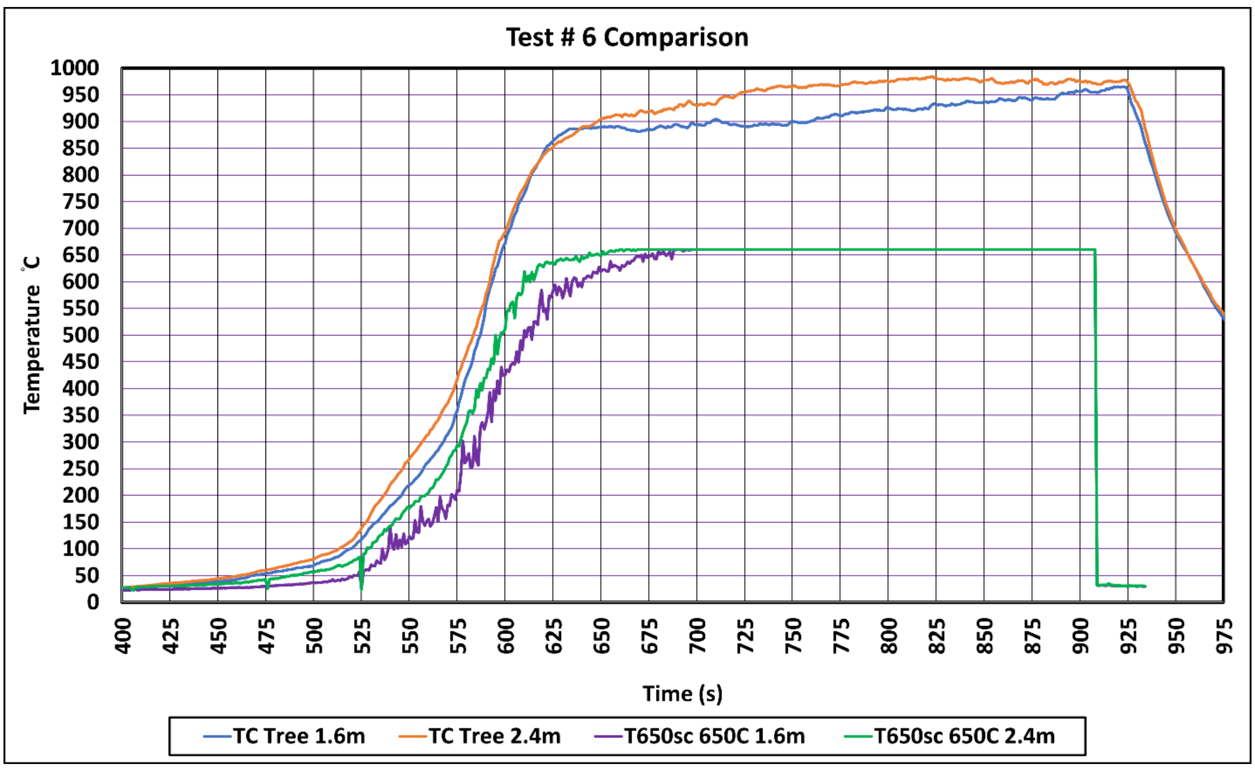
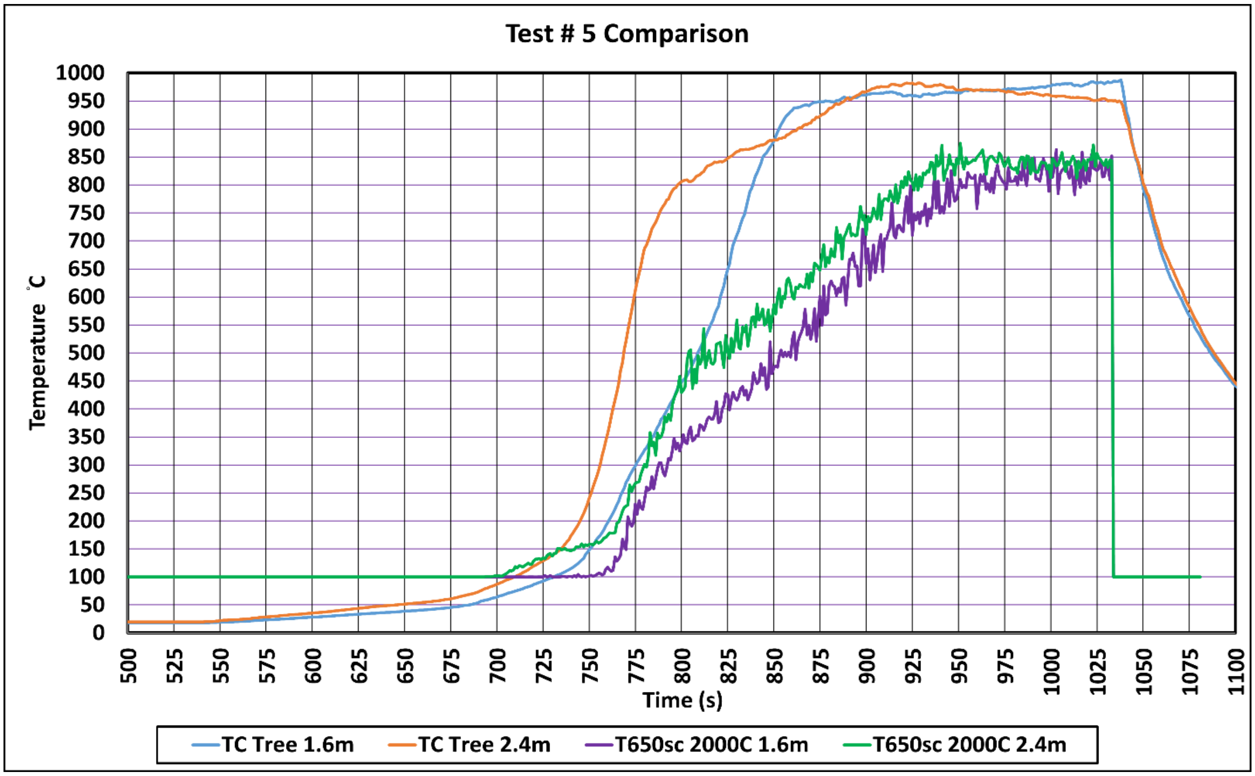


Figure 32- Comparison of temperature data extracted from video recorded by FLIR LWIR camera T650c with temperature range setting of up to 650°C and with temperature data recorded by thermocouples installed at 1.6 m and 2.4 m height in two separate actual room fire tests.



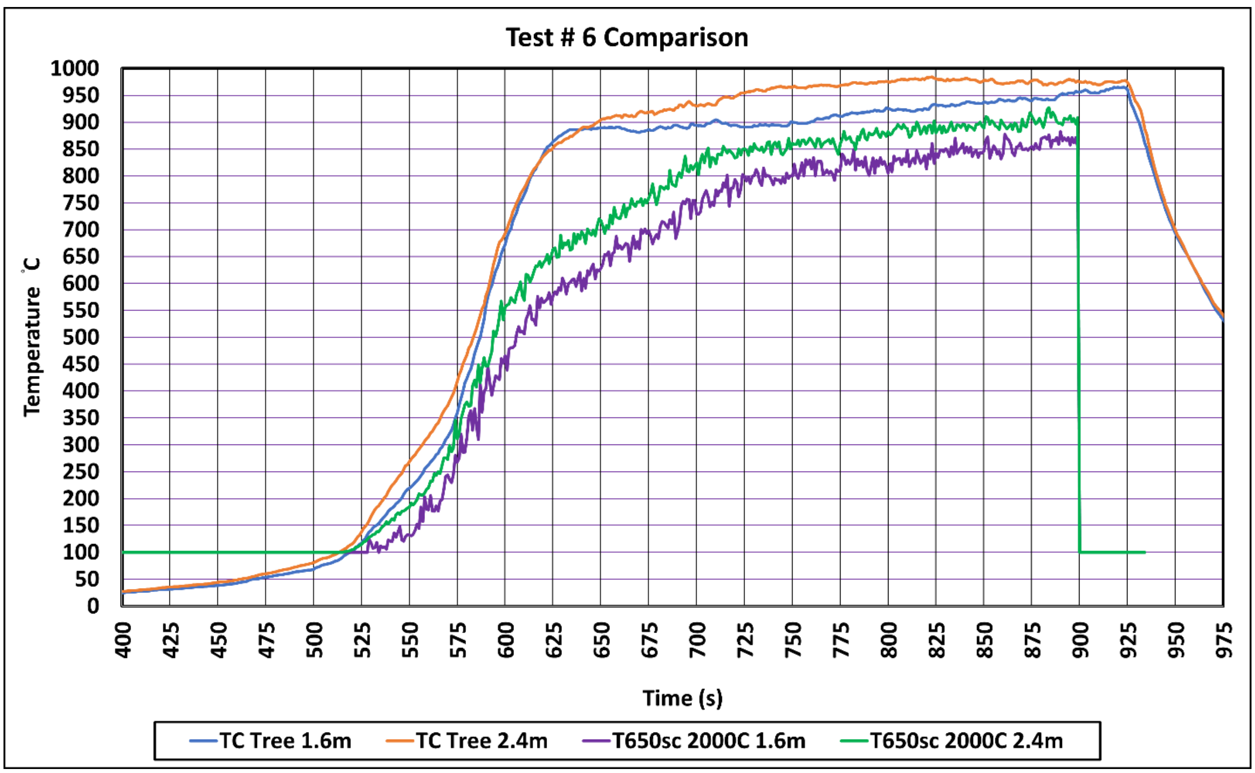


Figure 33- Comparison of temperature data extracted from video recorded by FLIR LWIR camera T650c with temperature range setting of up to 2000°C and with temperature data recorded by thermocouples installed at 1.6 m and 2.4 m height in two separate actual room fire tests.

5.3 Comparison of FLIR MWIR A8303sc and FLIR LWIR T650sc

In order to understand the differences between the performance of the two different IR camera technologies, MWIR and LWIR cameras in reading temperature data of a fire, we compared the temperature trends extracted from the recorded data by the two technologies after careful time-synchronization. Figure 33 and Figure 34 present this comparison between the two technologies for the same room fire tests. For Test #6, the overall temperature trends from both cameras are very similar, yet the readings and responses from the MWIR are slightly higher and faster than the LWIR. These differences are more apparent in Test #5, in which the MWIR camera experienced higher temperature, comparing to the LWIR camera.

It should be noted that the spectral range of the T650sc camera is 7.5 to 13.0 µm, which are not considered as the most suitable spectral range to characterize flames since many combustion products, such as water vapour, carbon dioxide, carbon monoxide and hydrocarbons are infrared-active in the MWIR band. Nonetheless, the LWIR band of 7.5 to 13.0 µm can collect thermal energy data in the combustion environment with the relatively low disturbance from soot and water vapour. However, thermal resolution of the LWIR band is generally lower than that of the MWIR particularly in the elevated temperature range.

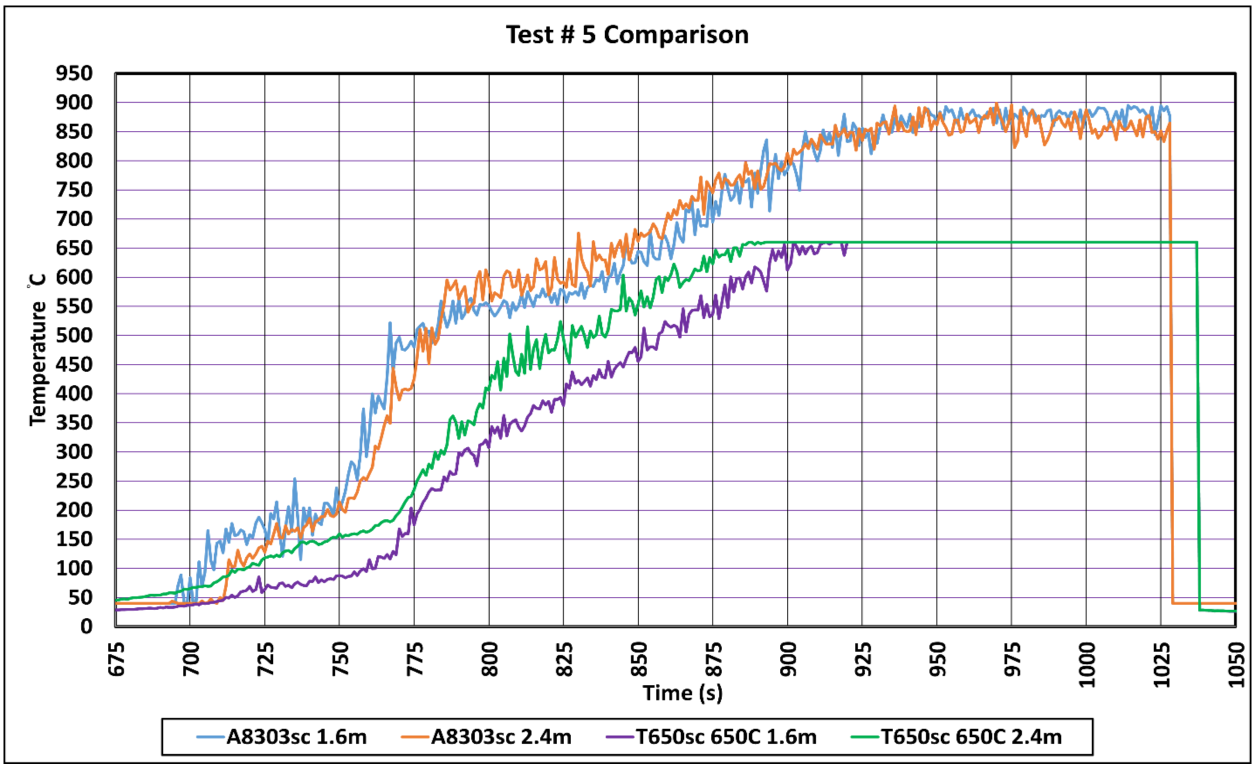
As a general conclusion, from Figure 33 and Figure 34, we can see that the both camera technologies behave similarly for the two room fire tests in terms of following temperature growth. The MWIR camera performs slightly faster and sharper than the LWIR camera, and both could be used for the readings for the elevated temperature close to flame temperature, yet the MWIR is more suitable. The small fluctuations in the trend of MWIR camera is also higher than the LWIR camera which is an indicator of higher thermal sensitivity of the MWIR camera in compared to LWIR ones.

5.4 Comparison of FLIR IR cameras and thermocouples

Now, we can compare the two technologies and thermocouples together. Figure 35 illustrates a general comparison of all these devices for the two room fire tests mentioned above. From this figure, it is clear that both camera worked similarly while the MWIR camera followed the thermocouple data with smaller temperature. By looking carefully at the graph of Test #6, from 150°C to 450°C, the MWIR and LWIR camera outputs are significantly similar to the thermocouple data. In the elevated temperature greater than 450°C, the readings from both cameras was affected by the thick smoke built up in the upper part of the test room, which lowered the transmittance of the radiant heat in both waveband of the MWIR and LWIR.

Also, the LWIR camera showed a slight delay in following the temperature rise. The MWIR camera captured the fire growth around 700s and 525s in Test #5 and #6 whereas the LWIR captured it around 750s and 530s. Although two technologies behave similarly, MWIR has sharper temperature rise more similar to the thermocouple data.

In summary, our in-house calibration of A8303sc resulted in the data comparable to the actual temperature over the entire duration of the room fire tests.



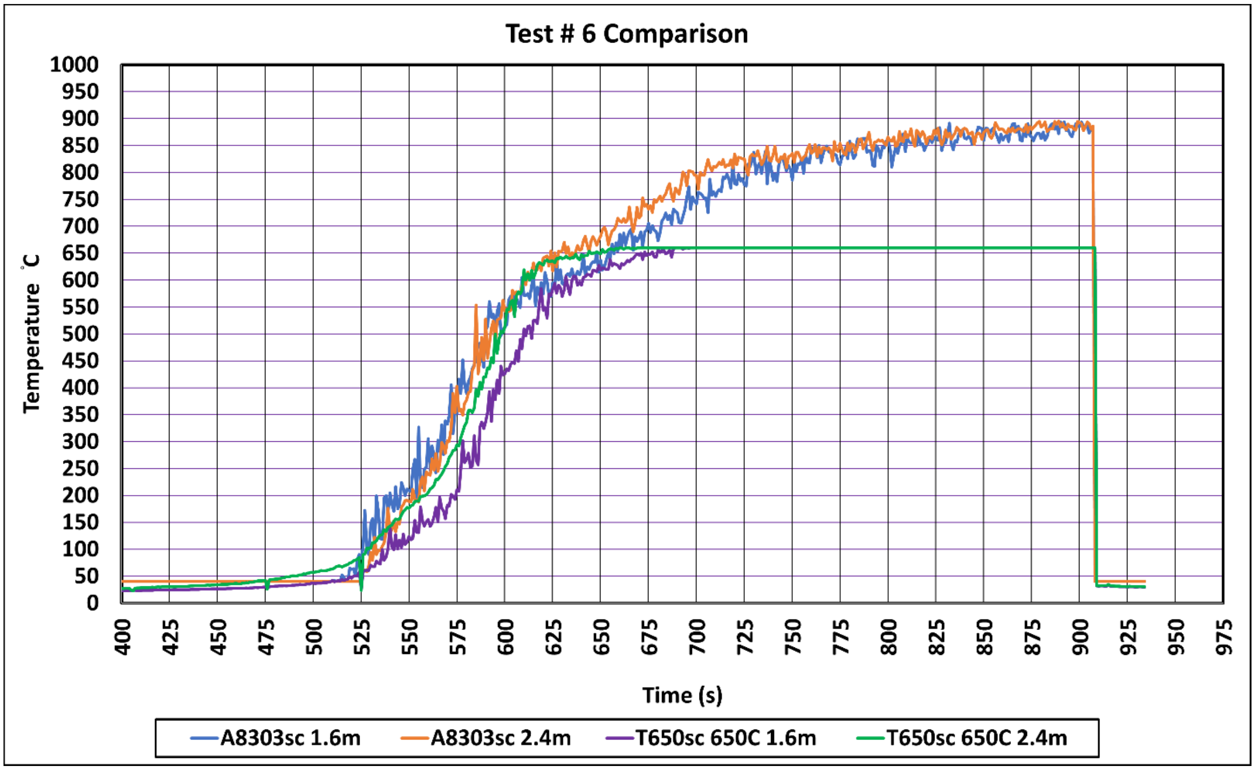
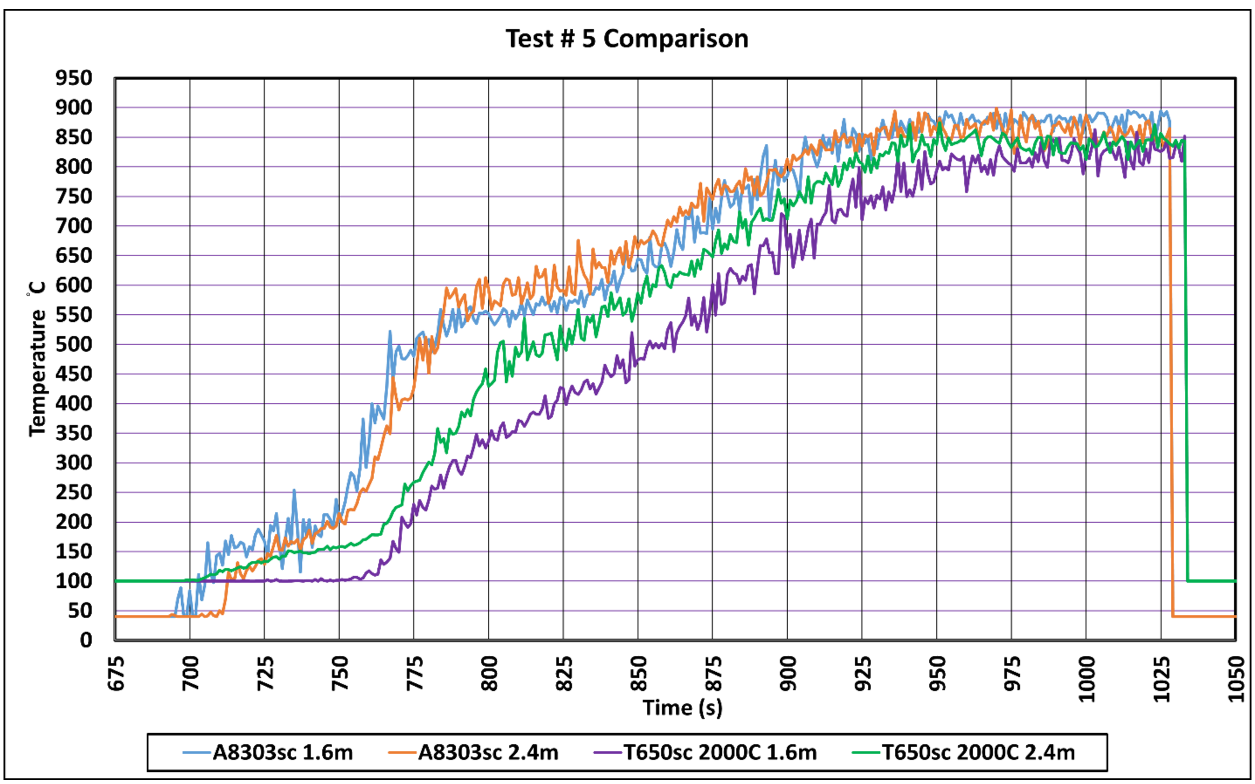


Figure 34- Comparison of temperature extracted from data recorded by a MWIR camera A8303sc with a LWIR camera T650sc when temperature range setting is set up to 650°C.



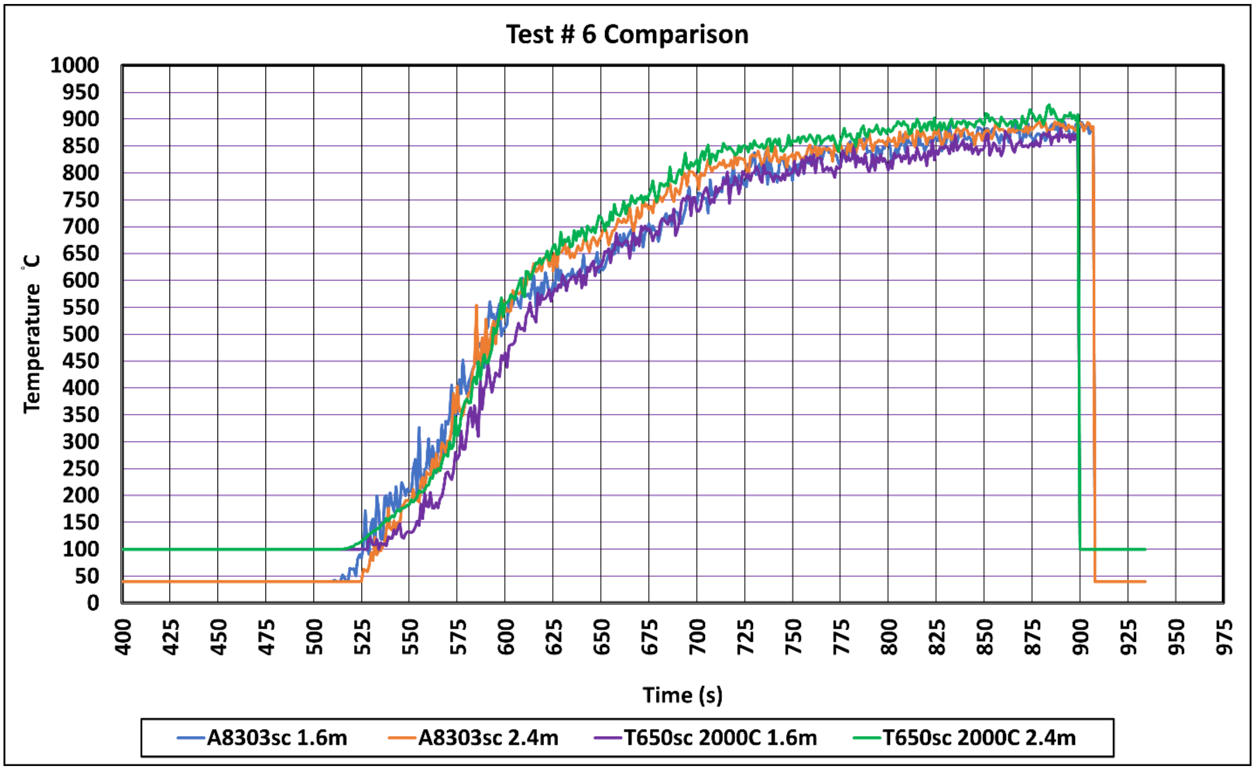
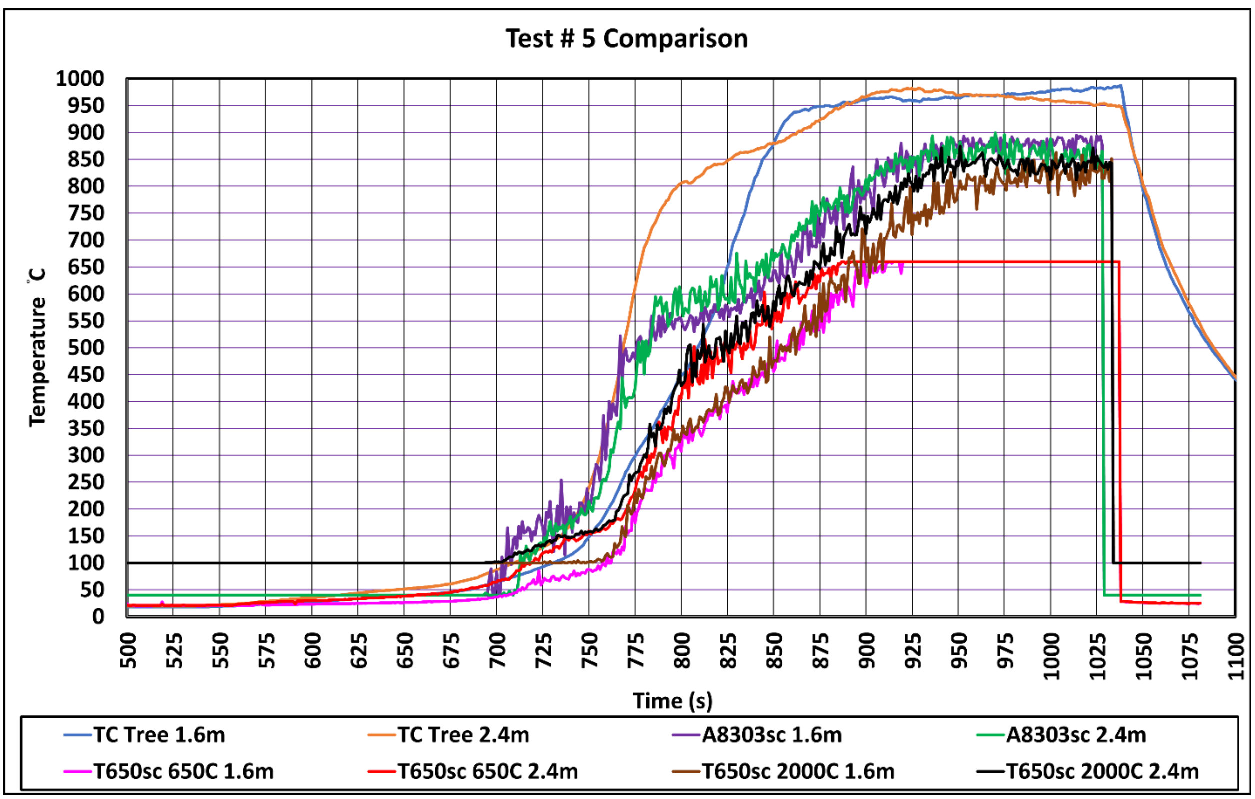


Figure 35- Comparison of temperature extracted from data recorded by a MWIR camera A8303sc with a LWIR camera T650sc when temperature range setting is set up to 2000°C.



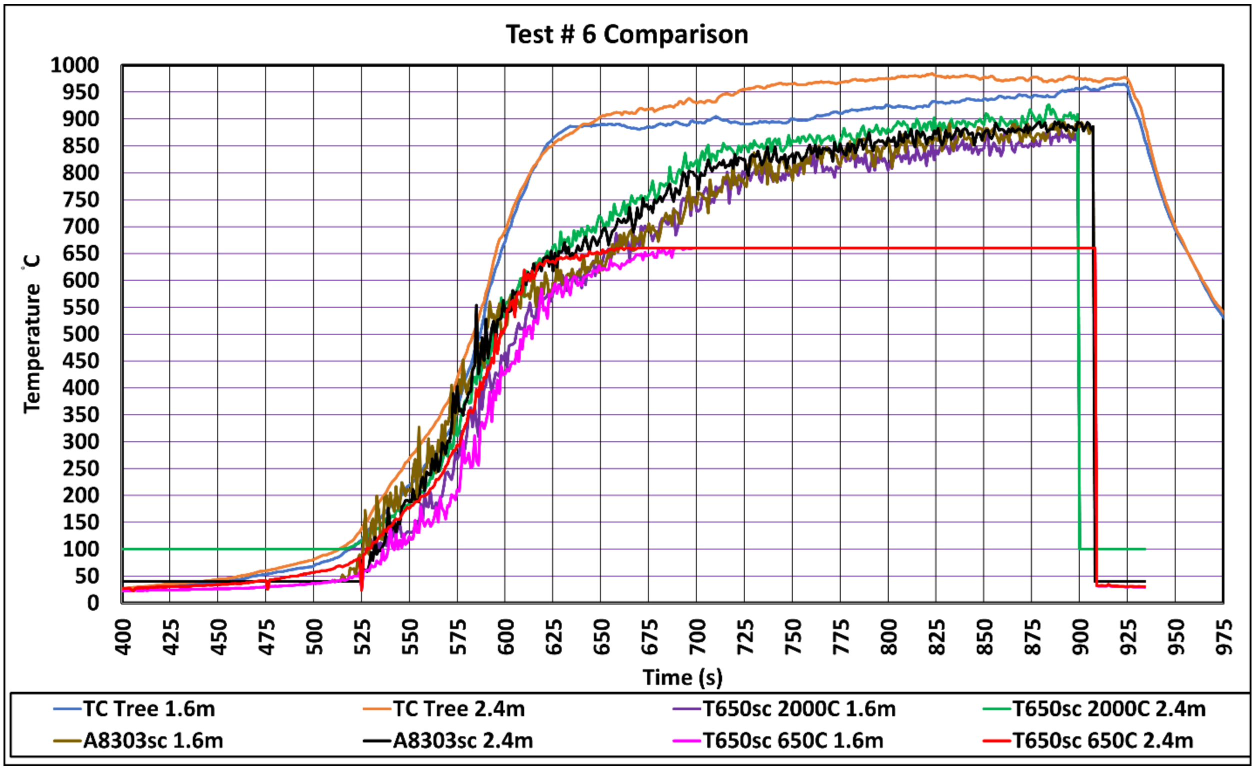


Figure 36- Comparison of temperature trend extracted from data recorded by IR cameras and thermocouples at 1.6 m and 2.4 m above the ground level in two actual room fire tests.

6 Discussions and Conclusion

A MWIR camera (FLIR A8303sc) was calibrated at the Fire Safety Unit (FSU) at National Research Council Canada (NRC) for the purpose of accurate measurements of temperature in a wide range covering from fire ignition to fully developed fire.

This report describes the importance, advantages, and disadvantages of the conducting in-house user calibration. The fundamentals behind the performance of FLIR IR cameras were provided for the in-house calibration. Also, this report provides complete steps of our user calibration using two blackbodies, which includes temperature settings of blackbodies, methods of calibration (standard vs. expert) using FLIR ResaechIR and CalibratIR software, saving and using our generated user calibration in actual test experiments.

The accuracy of our user calibration was evaluated by comparing with the data from factory calibrated LWIR cameras and thermocouples used in two full-scale room fire tests. The comparison verified that our in-house calibration performs equally or even better than the factory calibrated LWIR cameras. To compare and investigate our calibration performance further, we sent the in-house calibrated camera to the factory. The factory evaluated that our in-house calibration was accurate with the uncertainty range of ±2%. The factory calibration report is attached in Appendix A.

From the comparison with actual temperature data and the factory evaluation, it is concluded that the results from our in-house user calibration is acceptable within the standard tolerance range recommended by the FLIR company. Moreover, the in-house calibration made it possible to accurately measure the temperature range of 40°C to 1200°C without requiring filter replacement and by using the same integration time for the whole range.

This was one big step to show that non-invasive detection and monitoring of flame and smoke temperature could be made accurately using IR imagers that are user-calibrated for a wide range temperature including the elevated temperatures. This will enable the FSU to obtain accurate thermal measurements using the IR imagers even in outdoor testing or the conditions where thermocouple measurements are not possible.

7 References

[1] G. Neugebauer, E. Becklin, and A. R. Hyland, “Infrared sources of radiation,” *Annu. Rev. Astron. Astrophys.*, vol. 9, p. 67, 1971.

[2] A. Rogalski, “Infrared detectors: an overview,” *Infrared Phys. Technol.*, vol. 43, no. 3–5, pp. 187–

210, 2002.

[3] "Atmospheric electromagnetic opacity," *Wikimedia*. https://commons.wikimedia.org/wiki/File:Atmospheric_electromagnetic_opacity.svg

[4] "Infrared window," *Wikiperia*. https://en.wikipedia.org/wiki/Infrared_window

[5] "Comparing Sensitivity of Thermal Imaging Cameras Modules." https://www.flir.ca/discover/cores-components/Comparing-Sensitivity-of-Thermal-Imaging-Cameras-Modules/

Appendix A: Calibration Report from FLIR Company

This appendix contains calibration documents we received from FLIR company after ordering factory calibration for our FLIR thermal MWIR camera.

TELEDYNE FLIR
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Extended Calibration Certificate

Customer Name:	National Research Council Canada		
Customer Address:	1200 Montreal Road, M59 Ontario, Canada K1A 0R6		
Customer P.O. #:			
Notification Number:	[redacted]	Condition Received:	Out of tolerance
Model Number:	A8303sc	Received Date:	June 29, 2022
Serial Number:	[redacted]	Calibration Interval:	12 Months
Calibration Date:	August 24, 2022	Calibration Due:	August 24, 2023

It is hereby certified that the above equipment was calibrated by Teledyne FLIR Systems, Inc. using NIST traceable equipment as listed below and meets Teledyne FLIR Systems, Inc. calibration specifications.

Teledyne FLIR Systems, Inc. imaging radiometers are calibrated for either absolute or relative temperature measurements or both. This process is accomplished by characterizing the detector response to a series of known temperature "blackbodies." During the calibration process, the radiometer signal processor's output is calibrated so that it has a direct correlation to the temperature differences created by the various blackbodies.

Teledyne FLIR Systems, Inc. recommends that its radiometric products be re-calibrated annually.

Calibration Procedure included with QOP-085-11, *Customer Returns, Service, and Repair (Instruments)*

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ISO 9001 Certified

TELEDYNE FLIR
Everywhereyoulook™

Model: A8303sc Serial Number: [redacted]

As Received Calibration Data

Calibration Conditions:
Temperature: *22C* Humidity: *49%*
Lens: *50mm*

Range	Nom Temp/Tol (°C)	Measured Temperature	Difference
-20ºC-55 ºC	2.0°C / ± 2.0°C	3.4°C	1.4°C
-20ºC-55 ºC	10.0°C / ± 2.0°C	11.0°C	1.0°C
-20ºC-55 ºC	35.0°C / ± 2.0°C	36.1°C	1.1°C
-20ºC-55 ºC	55.0°C / ± 2.0°C	57.3°C	2.3°C
10ºC-90 ºC	10.0°C / ± 2.0°C	11.1°C	1.1°C
10ºC-90 ºC	35.0°C / ± 2.0°C	36.1°C	1.1°C
10ºC-90 ºC	55.0°C / ± 2.0°C	56.4°C	1.4°C
10ºC-90 ºC	80.0°C / ± 2.0°C	82.0°C	2.0°C
35ºC-150 ºC	35.0°C / ± 2.0°C	37.8°C	2.8°C
35ºC-150 ºC	55.0°C / ± 2.0°C	57.1°C	2.1°C
35ºC-150 ºC	80.0°C / ± 2.0°C	82.0°C	2.0°C
35ºC-150 ºC	110.0°C / ± 2.2°C	111.3°C	1.3°C
35ºC-150 ºC	150.0°C / ± 3.0°C	151.4°C	1.4°C
80ºC-200 ºC	80.0°C / ± 2.0°C	83.0°C	3.0°C
80ºC-200 ºC	110.0°C / ± 2.2°C	111.8°C	1.8°C
80ºC-200 ºC	150.0°C / ± 3.0°C	151.3°C	1.3°C
80ºC-200 ºC	200.0°C / ± 4.0°C	200.5°C	0.5°C
150ºC-350 ºC	150.0°C / ± 3.0°C	142.5°C	-7.6°C
150ºC-350 ºC	200.0°C / ± 4.0°C	196.8°C	-3.2°C
150ºC-350 ºC	250.0°C / ± 5.0°C	251.7°C	1.7°C
150ºC-350 ºC	280.0°C / ± 5.6°C	283.9°C	3.9°C
150ºC-350 ºC	350.0°C / ± 7.0°C	355.9°C	5.9°C

Approvals:
Calibration Technician: Phil Babcock
Quality Technician: Ed Fana

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TELEDYNE FLIR
Everywhereyoulook™

Model: A8303 Serial Number [redacted]

As Left Calibration Data

Calibration Conditions:
Temperature: *21 C* Humidity: *56%*
Lens: *50mm*

Range	Nom Temp/Tol (°C)	Measured Temperature	Difference
-20°C-55 °C	2.0°C / ± 2.0°C	1.8°C	-0.2°C
-20°C-55 °C	10.0°C / ± 2.0°C	9.0°C	-1.0°C
-20°C-55 °C	35.0°C / ± 2.0°C	34.8°C	-0.2°C
-20°C-55 °C	55.0°C / ± 2.0°C	55.5°C	0.5°C
10°C-90 °C	10.0°C / ± 2.0°C	11.1°C	1.1°C
10°C-90 °C	35.0°C / ± 2.0°C	35.4°C	0.4°C
10°C-90 °C	55.0°C / ± 2.0°C	55.1°C	0.1°C
10°C-90 °C	80.0°C / ± 2.0°C	80.0°C	0.0°C
35°C-150 °C	35.0°C / ± 2.0°C	36.0°C	1.0°C
35°C-150 °C	55.0°C / ± 2.0°C	55.5°C	0.5°C
35°C-150 °C	80.0°C / ± 2.0°C	80.2°C	0.2°C
35°C-150 °C	110.0°C / ± 2.2°C	109.6°C	-0.4°C
35°C-150 °C	150.0°C / ± 3.0°C	150.1°C	0.1°C
80°C-200 °C	80.0°C / ± 2.0°C	80.5°C	0.5°C
80°C-200 °C	110.0°C / ± 2.2°C	109.5°C	-0.5°C
80°C-200 °C	150.0°C / ± 3.0°C	149.4°C	-0.6°C
80°C-200 °C	200.0°C / ± 4.0°C	199.8°C	-0.2°C
150°C-350 °C	150.0°C / ± 3.0°C	150.5°C	0.5°C
150°C-350 °C	200.0°C / ± 4.0°C	199.8°C	-0.2°C
150°C-350 °C	250.0°C / ± 5.0°C	248.7°C	-1.3°C
150°C-350 °C	280.0°C / ± 5.6°C	279.0°C	-1.0°C
150°C-350 °C	350.0°C / ± 7.0°C	349.6°C	-0.4°C

Approvals:
Calibration Technician: ____________
Quality Technician: ____________

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TELEDYNE FLIR
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Model: A8303sc Serial Number: [redacted]

As Received Calibration Data

Calibration Conditions:
Temperature: *22C* Humidity: *49%*
Lens: *50mm ND2*

Range	Nom Temp/Tol (°C)		Measured Temperature	Difference
250°C-600 °C	250.0°C	/ ± 5.00°C	N/A	
250°C-600 °C	280.0°C	/ ± 5.60°C	N/A	
250°C-600 °C	350.0°C	/ ± 7.00°C	N/A	
250°C-600 °C	500.0°C	/ ± 10.00°C	N/A	
250°C-600 °C	600.0°C	/ ± 12.00°C	N/A	
500°C-1200 °C	500.0°C	/ ± 10.00°C	N/A	
500°C-1200 °C	600.0°C	/ ± 12.00°C	N/A	
500°C-1200 °C	700.0°C	/ ± 14.00°C	N/A	
500°C-1200 °C	850.0°C	/ ± 17.00°C	N/A	
500°C-1200 °C	1100.0°C	/ ± 22.00°C	N/A	
850°C-2000 °C	850.0°C	/ ± 17.00°C	N/A	
850°C-2000 °C	1100.0°C	/ ± 22.00°C	N/A	
850°C-2000 °C	1500.0°C	/ ± 30.00°C	N/A	
850°C-2000 °C	2000.0°C	/ ± 40.00°C	N/A	

Approvals:
Calibration Technician: Phil Balint
Quality Technician: Ed Jones

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TELEDYNE FLIR
Everywhereyoulook™

Model: A8303 Serial Number [redacted]

As Left Calibration Data

Calibration Conditions:
Temperature: *21 C* Humidity: *56%*
Lens: *50mm with ND2*

Range	Nom Temp/Tol (°C)		Measured Temperature	Difference
250°C-600 °C	250.0°C	/ ± 5.00°C	250.9°C	0.9°C
250°C-600 °C	280.0°C	/ ± 5.60°C	281.0°C	1.0°C
250°C-600 °C	350.0°C	/ ± 7.00°C	349.6°C	-0.4°C
250°C-600 °C	500.0°C	/ ± 10.00°C	496.1°C	-3.9°C
250°C-600 °C	600.0°C	/ ± 12.00°C	600.0°C	0.0°C
500°C-1200 °C	500.0°C	/ ± 10.00°C	500.0°C	0.0°C
500°C-1200 °C	600.0°C	/ ± 12.00°C	600.2°C	0.2°C
500°C-1200 °C	700.0°C	/ ± 14.00°C	698.8°C	-1.2°C
500°C-1200 °C	850.0°C	/ ± 17.00°C	847.8°C	-2.2°C
500°C-1200 °C	1100.0°C	/ ± 22.00°C	1106.5°C	6.5°C
850°C-2000 °C	850.0°C	/ ± 17.00°C	853.4°C	3.4°C
850°C-2000 °C	1100.0°C	/ ± 22.00°C	1098.4°C	-1.6°C
850°C-2000 °C	1500.0°C	/ ± 30.00°C	1491.3°C	-8.7°C
850°C-2000 °C	2000.0°C	/ ± 40.00°C	2004.0°C	4.0°C

Approvals:
Calibration Technician: [signature]
Quality Technician: [signature]

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Model: A8303sc Serial Number: [redacted]

As Received Calibration Data

Calibration Conditions:
Temperature: *22C* Humidity: *49%*
Lens: *100mm*

Range	Nom Temp/Tol (°C)	Measured Temperature	Difference
-20ºC-55 ºC	2.0°C / ± 2.0°C	N/A	
-20ºC-55 ºC	10.0°C / ± 2.0°C	N/A	
-20ºC-55 ºC	35.0°C / ± 2.0°C	N/A	
-20ºC-55 ºC	55.0°C / ± 2.0°C	N/A	
10ºC-90 ºC	10.0°C / ± 2.0°C	N/A	
10ºC-90 ºC	35.0°C / ± 2.0°C	N/A	
10ºC-90 ºC	55.0°C / ± 2.0°C	N/A	
10ºC-90 ºC	80.0°C / ± 2.0°C	N/A	
35ºC-150 ºC	35.0°C / ± 2.0°C	N/A	
35ºC-150 ºC	55.0°C / ± 2.0°C	N/A	
35ºC-150 ºC	80.0°C / ± 2.0°C	N/A	
35ºC-150 ºC	110.0°C / ± 2.2°C	N/A	
35ºC-150 ºC	150.0°C / ± 3.0°C	N/A	
80ºC-200 ºC	80.0°C / ± 2.0°C	N/A	
80ºC-200 ºC	110.0°C / ± 2.2°C	N/A	
80ºC-200 ºC	150.0°C / ± 3.0°C	N/A	
80ºC-200 ºC	200.0°C / ± 4.0°C	N/A	
150ºC-350 ºC	150.0°C / ± 3.0°C	N/A	
150ºC-350 ºC	200.0°C / ± 4.0°C	N/A	
150ºC-350 ºC	250.0°C / ± 5.0°C	N/A	
150ºC-350 ºC	280.0°C / ± 5.6°C	N/A	
150ºC-350 ºC	350.0°C / ± 7.0°C	N/A	

Approvals:
Calibration Technician: ____________
Quality Technician: ____________

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Model: A8303 Serial Number: [redacted]

As Left Calibration Data

Calibration Conditions:

Temperature: *21 C* Humidity: *56%*

Lens: *100mm*

Range	Nom Temp/Tol (°C)	Measured Temperature	Difference
-20°C-55 °C	2.0°C / ± 2.0°C	0.1°C	-1.9°C
-20°C-55 °C	10.0°C / ± 2.0°C	8.1°C	-2.0°C
-20°C-55 °C	35.0°C / ± 2.0°C	33.2°C	-1.8°C
-20°C-55 °C	55.0°C / ± 2.0°C	54.5°C	-0.5°C
10°C-90 °C	10.0°C / ± 2.0°C	11.8°C	1.8°C
10°C-90 °C	35.0°C / ± 2.0°C	35.1°C	0.1°C
10°C-90 °C	55.0°C / ± 2.0°C	54.5°C	-0.5°C
10°C-90 °C	80.0°C / ± 2.0°C	79.7°C	-0.3°C
35°C-150 °C	35.0°C / ± 2.0°C	36.3°C	1.3°C
35°C-150 °C	55.0°C / ± 2.0°C	55.2°C	0.2°C
35°C-150 °C	80.0°C / ± 2.0°C	79.8°C	-0.2°C
35°C-150 °C	110.0°C / ± 2.2°C	109.1°C	-0.9°C
35°C-150 °C	150.0°C / ± 3.0°C	149.6°C	-0.4°C
80°C-200 °C	80.0°C / ± 2.0°C	80.3°C	0.3°C
80°C-200 °C	110.0°C / ± 2.2°C	109.1°C	-0.9°C
80°C-200 °C	150.0°C / ± 3.0°C	148.9°C	-1.1°C
80°C-200 °C	200.0°C / ± 4.0°C	199.2°C	-0.8°C
150°C-350 °C	150.0°C / ± 3.0°C	149.9°C	-0.1°C
150°C-350 °C	200.0°C / ± 4.0°C	199.1°C	-0.9°C
150°C-350 °C	250.0°C / ± 5.0°C	248.7°C	-1.3°C
150°C-350 °C	280.0°C / ± 5.6°C	278.1°C	-1.9°C
150°C-350 °C	350.0°C / ± 7.0°C	348.4°C	-1.6°C

Approvals:

Calibration Technician: ______________

Quality Technician: ______________

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TELEDYNE FLIR
Everywhereyoulook™

Model: A8303sc Serial Number: [redacted]

As Received Calibration Data

Calibration Conditions:
Temperature: *22C* Humidity: *49%*
Lens: *100mm ND2*

Range	Nom Temp/Tol (°C)		Measured Temperature	Difference
250°C-600 °C	250.0°C	/ ± 5.00°C	N/A	
250°C-600 °C	280.0°C	/ ± 5.60°C	N/A	
250°C-600 °C	350.0°C	/ ± 7.00°C	N/A	
250°C-600 °C	500.0°C	/ ± 10.00°C	N/A	
250°C-600 °C	600.0°C	/ ± 12.00°C	N/A	
500°C-1200 °C	500.0°C	/ ± 10.00°C	N/A	
500°C-1200 °C	600.0°C	/ ± 12.00°C	N/A	
500°C-1200 °C	700.0°C	/ ± 14.00°C	N/A	
500°C-1200 °C	850.0°C	/ ± 17.00°C	N/A	
500°C-1200 °C	1100.0°C	/ ± 22.00°C	N/A	
850°C-2000 °C	850.0°C	/ ± 17.00°C	N/A	
850°C-2000 °C	1100.0°C	/ ± 22.00°C	N/A	
850°C-2000 °C	1500.0°C	/ ± 30.00°C	N/A	
850°C-2000 °C	2000.0°C	/ ± 40.00°C	N/A	

Approvals:
Calibration Technician: Phil Babcock
Quality Technician: Ed Jones

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TELEDYNE FLIR
Everywhereyoulook™

Model: A8303 Serial Number: [redacted]

As Left Calibration Data

Calibration Conditions:
Temperature: *21 C* Humidity: *56%*
Lens: *100mm ND2*

Range	Nom Temp/Tol (°C)		Measured Temperature	Difference
250ºC-600 ºC	250.0°C	/ ± 5.00°C	250.1°C	0.1°C
250ºC-600 ºC	280.0°C	/ ± 5.60°C	280.6°C	0.6°C
250ºC-600 ºC	350.0°C	/ ± 7.00°C	349.9°C	-0.1°C
250ºC-600 ºC	500.0°C	/ ± 10.00°C	497.1°C	-2.9°C
250ºC-600 ºC	600.0°C	/ ± 12.00°C	597.0°C	-3.0°C
500ºC-1200 ºC	500.0°C	/ ± 10.00°C	503.9°C	3.9°C
500ºC-1200 ºC	600.0°C	/ ± 12.00°C	598.3°C	-1.7°C
500ºC-1200 ºC	700.0°C	/ ± 14.00°C	693.0°C	-7.0°C
500ºC-1200 ºC	850.0°C	/ ± 17.00°C	845.7°C	-4.3°C
500ºC-1200 ºC	1100.0°C	/ ± 22.00°C	1095.2°C	-4.8°C
850ºC-2000 ºC	850.0°C	/ ± 17.00°C	849.1°C	-0.9°C
850ºC-2000 ºC	1100.0°C	/ ± 22.00°C	1094.6°C	-5.4°C
850ºC-2000 ºC	1500.0°C	/ ± 30.00°C	1484.0°C	-16.0°C
850ºC-2000 ºC	2000.0°C	/ ± 40.00°C	1987.8°C	-12.2°C

Approvals:
Calibration Technician: ____________
Quality Technician: ____________

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Note that customer Calibration services are performed using one or more of the blackbodies listed in the table below. Teledyne FLIR Commercial Systems, Inc. blackbodies are measurement standards calibrated by Teledyne FLIR or the OEM manufacturer.

Cal ID #'s	M&TE Equipment Used	Recall Date	Certification #
53059 / 53060	BlackBody Source	Jul-23	CC-22-006
53061 / 53062	BlackBody Source	Jul-23	CC-22-007
53063 / 53064	BlackBody Source	Jul-23	CC-22-008
53053 / 53054	BlackBody Source	Jul-23	CC-22-005
53055 / 53056	BlackBody Source	Jul-23	CC-22-004
103563/103606	BlackBody Source	Jul-23	CC-22-009
53067 / 53068	BlackBody Source	Jul-23	CC-22-010
53069 / 53070	BlackBody Source	Jul-23	CC-22-011
53243 / 53244	BlackBody Source	Jul-23	CC-22-012
53071 / 53074	BlackBody Source	Jul-23	CC-22-013
53050	BlackBody Source	Jul-23	CC-22-003

Cal ID #'s	M&TE Equipment Used	Recall Date	Certification #
53083/ 53085	BlackBody Source	Jul-23	CC-22-014
53129 / 53131	BlackBody Source	Jul-23	CC-22-015
53128/ 53130	BlackBody Source	Jul-23	CC-22-016
53223 / 53226	BlackBody Source	Jul-23	CC-22-017
53230 / 53228	BlackBody Source	Jul-23	CC-22-018
53222 / 53225	BlackBody Source	Jul-23	CC-22-019
53221 / 53224	BlackBody Source	Jul-23	CC-22-020
53098 / 53096	BlackBody Source	Jul-23	CC-22-021
53097	BlackBody Source	Jul-23	CC-22-022
53231	BlackBody Source	Jul-23	CC-22-023

The devices listed in the table below are used in the calibration of the Black bodies listed in the table above.

Equipment	Serial Number	Traceable NIST Report Number	Last Cal Date	Next Cal Date	Cal Ratio
ASL PRT T-100-450 (ID # 53355)	[redacted]	[redacted]	5/23/2022	5/23/2023	80:1
ASL Digital Indicator F150 (ID # 53357)	[redacted]	[redacted]	5/23/2022	5/23/2023	80:1
Thermocouple JMS TYPE "S" (ID # 53356)	[redacted]	[redacted]	5/23/2022	5/23/2023	5:1
Thermocouple JMS TYPE "B" (ID # 158332)	[redacted]	[redacted]	5/23/2022	5/23/2023	5:1

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