CHAPTER 4

CALIBRATIONS AND CONTROL SOFTWARE[[1]](#footnote-1)

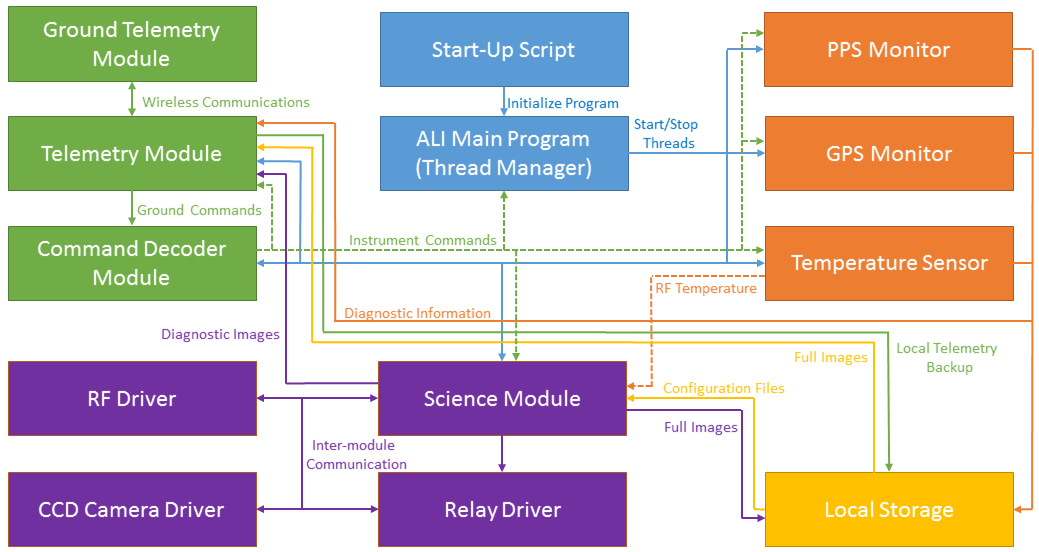
# 4.1 Introduction

This chapter focuses on a discussion of the control software developed for the ALI stratospheric balloon flight, as well as the calibration and performance evaluation of the instrument. For the calibration, the AOTF is first characterized separately from the ALI optical system and detector, and then the fully assembled instrument calibration is presented.

# 4.2 Control Software

During the stratospheric balloon flight, software is required in order to control the instrument from the ground for remote operation. Two separate software packages were developed to accomplish the communication and control systems required for the mission. First, a ground system, commonly known as Ground Support Equipment, or “GSE”, was developed to provide communication to the instrument including the receipt of diagnostic information and images, and the capability to provide control commands. The second software system was the onboard system that controls the instrument operations.

The GSE is responsible for establishing communication with ALI, handling any loss of information during data transfer, decoding the data from the ALI flight software, as well as uploading commands to the instrument. The onboard control system is more complicated with several different modules to handle the different aspects of the hardware and control systems. The onboard computer is a VersaLogic PC-104 OCELOT, which has fanless operation, a thermal operating range of -40 to 85◦C, and runs a Debian Linux operating system. Multi-threaded C++ based software developed specifically for ALI controls the hardware and runs the data collection operating modes. This flight software contains five different modules to handle different functions of the system. The five modules are the main module, communication module, diagnostics module, science module, and local storage represented in Figure 4-1 by blue, green, orange, purple, and yellow respectively. A brief overview of each follows.



**Figure 4-1**: A complete flow diagram showing interaction between all the of ALI software modules on the on board ALI flight computer.

The main module consists of a bash script which initiates the ALI C++ flight program during startup and can be restarted from the ground upon a software failure. Once the main program has been started by the script, the thread manager initializes all of the individual threads for the other processes and then waits for a termination command to close the ALI flight software.

The first module started by the thread manager is the communications module which operates the telemetry or communication between other modules as well interactions with the ground control software. The module sends and receives all data packets that are outgoing and incoming through UDP protocol as required by the CSA and CNES specifications. Also, data rate limits were imposed on the instruments to avoid one instrument using all the bandwidth to transfer data from the gondola. For ALI the limit was 100,000 bits per second. The communication module was responsible for verifying that this limit was obeyed when encoding into packets and sending them to the ground. Also, uploaded commands are decoded and sent to the command decoder, which takes all the incoming commands from the ground, parses the information, and sends the commands to the proper modules. A full list of commands can be found in section B.1

The diagnostic module manages the Global Positioning System (GPS) information, pulse per second ping, and voltage and temperature sensors. The GPS monitor records the current location and height of the instrument from the front of ALI optical instrument. The pulse per second is a signal that is sent out from the gondola's SIREN module (a proprietary device used for the gondola's communications and telemetry system) every second. It is a constant signal between all instruments on board to synchronize data collection. The voltage sensors provide monitoring to ensure that the voltage levels stay within the electronics specified ranges. Lastly, the temperature sensor module reads all of the temperature sensors from a one-line temperature sensing device, where all temperature sensors are connected with a simple RS-232 connection. The locations of the temperature sensors can be seen in Table 4-1 and the locations attempt to achieve a complete temperature profile of the instrument. All information gathered by the diagnostic module is sent to the telemetry system so the ground user can determine the state of the system and make any required changes. The data is also stored on the local hard drive (solid state) onboard ALI for use when ALI is recovered after the flight.

**Table 4-1**: Location of ALI temperature sensors.

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| Number | Sensor Location |
| 1 | Aluminum wall of electronics case |
| 2 | Cooling plat of RF Driver |
| 3 | OCELOT CPU heatsink |
| 4 | Aluminum wall of power supply case |
| 5 | 5 V power supply transducer |
| 6 | 12 V power supply transducer |
| 7 | Front of ALI baffle just inside system |
| 8 | On the CCD camera |

The science module operated the ALI instrument, the acquisition of data, and directly controls the relay to the RF driver and the QSI CCD camera. The science module loads program defaults upon startup from local storage or program settings can be altered from ground control. Each of the modes for data acquisition has its own configuration file and the supported modes are a calibration mode, an aerosol mode, an H2O mode, an O2 mode, a constant exposure time aerosol mode, and a custom mode. The details for these mode can be found in appendix B.2.

When the science operations are enabled ALI loads an operational mode as specified from the ground. The science mode controls all of the hardware and processes the imaging cycle. Two types of images are created. Full images that contain the entire image are sent to local storage due to bandwidth considerations, and diagnostic images are transmitted to the ground. These contain the required information to achieve minimal level of success from the flight in case the local solid state drive is not recoverable after the balloon flight due to a crash landing, water damage, etc. When the mode is completed the same mode is repeated unless the instrument has received a command to stop acquiring images or is queued to start another mode.

Each diagnostic image contains five complete vertical columns of measurements with statistics on the entire image, including percentages of saturated and under-saturated pixels, as well as the location and time of the measurement and the current state of ALI. The software was configured such that any extra bandwidth that is not allocated to other processes is used to transmit complete images to the ground.

# 4.3 AOTF Calibration

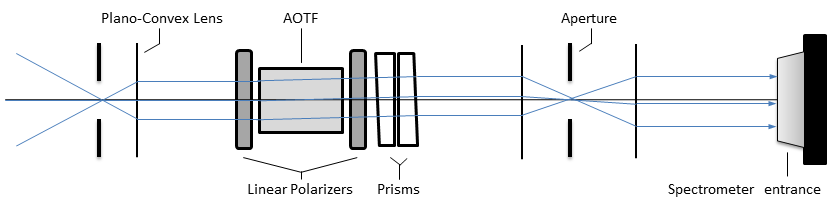
The calibration of the AOTF is presented within this this section. As noted previously, the AOTF was purchased from Brimrose of America and the complete specifications can be found in appendix A.1.3. The calibrations preformed on the AOTF are:

* Tuning curve analysis
* Point spread function analysis
* Diffraction efficiency determination.

## 4.3.1 Tuning Curve Analysis

The tuning curve relates the applied RF wave to the diffracted wavelength, and must be accurately known to determine the wavelength being measured, as this directly affects the aerosol retrieval. The form of the tuning curve is given in Equation 3.32. To determine the tuning curve for the AOTF, a test optical set up was devised in the lab to measure the central diffracted wavelength as a function of the selected RF.

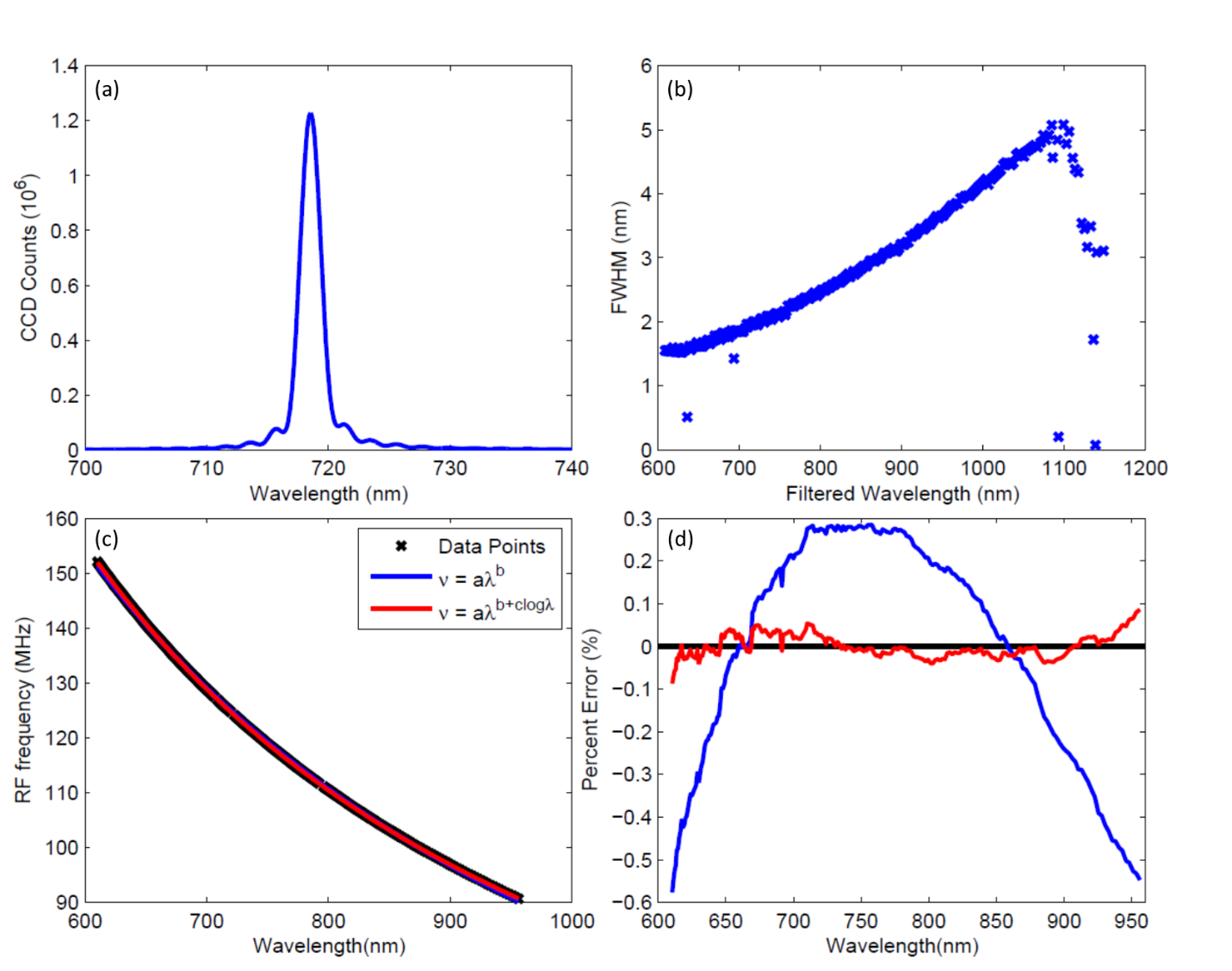
For this analysis, a telecentric test layout was used, the details of which are described in section 3.3.2. An advantage of the telecentric testing layout for the AOTF characterization is that the wavelength dependence of the acousto-effect from the incident angle, noted in Equation 3.32, is removed since all the lines of sight enter the AOTF with the same angular spread. The experimental set up consisted of the AOTF centered between two 100 mm focal length lenses to optimally fill the AOTF aperture. Linear polarizers were inserted before and after the AOTF to remove the unwanted polarization states. An aperture was set up in front and behind the AOTF in the optical chain at the focal length of the front and back lenses respectively and opened to 5 mm to complete the telecentric experimental layout. The high front end f-number of 20 required long integration times to capture sufficient signal but provides a much higher degree of telecentricity. Two prisms were used to compensate for the 2.7◦ off axis bending to set the light parallel to the optical path. A standard 100 W tungsten halogen bulb was used as a light source. The front end optics had no magnification and back optics were used to match the f-number of the spectrometer's input optics. The layout can be seen in Figure 4-2.



**Figure 4-2**: Telecentric test experiential setup for AOTF parameter determination. All lenses and apertures are represented by the same symbol.

The output is passed into a HORIBA iHR320 spectrometer with a 1200 lines/mm grating blazed at 750 nm and is imaged on a Synapse 354308 front-illuminated CCD detector with 1024x256 pixels. The CCD is thermoelectricity cooled to -75◦C to reduce any significant dark current contributions to the measurements. The signal entering the spectrometer optics were well collimated and limited the amount of stray light.

Images were taken at a set of RFs spaced every 150 kHz from 160 MHz to 75 MHz nominally corresponding to a 1 nm resolution. The spectral images were recorded with the spectrometer slit at 0.5 mm making the minimum Full Width Half Max (FWHM) of the spectrometer 1.175 nm, less than the minimum factory specification for the AOTF spectral resolution of 1.6 nm. Note that the final recorded spectra are a convolution of the PSF of the AOTF and spectrometer and this will have a small effect on the determined spectral resolution. At each RF, two images were taken with a 15 second exposure time: one with the AOTF in the “on” state and another with the AOTF in the “off” state. The stray light, dark current, and the DC bias are recorded in the image with the AOTF turned off and can be removed from the final image by subtraction. Since the recorded spectra are spatially aligned in the images all of the rows of the CCD are summed together to get the total count measurement at each wavelength. The maximum value of each spectra is taken to be the central diffracted wavelength through the AOTF at each respective RF. A typical spectral measurement result can be seen in **Error! Reference source not found.**a.



**Figure 4-3**: (a) A row averaged image taken from the AOTF of the point spread function when the tuning frequency of the AOTF was at 124.96 MHz. (b) The FWHM for each of the determined wavelengths for the AOTF. The FWHM at 600 nm is 1.5 nm and as the wavelengths get longer the FWHM increases to 4.9 nm at 1080 nm. (c) The calibration curves for the AOTF RF versus the diffracted wavelength which contains the data points recorded and fit curves. (d) The percent error with respect to the measured frequency for the two best fit curves in the previous panel. Originally published as Figure 6 in *Elash et al.* (2016).

The maximum values from each of the images were determined along with the corresponding wavelengths. The function form of the tuning curve from section 3.2.4 (Equation 3.32) shows that the wavelength and the RF are inversely related. Although this is approximately the case with this measured data, it was noted that the curve empirically fit a power function of the form

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|  | (4.1) |

This fit provides an agreement with the measurements across the spectral range to better than 0.6%. An improved fit was provided by a modified power function in the form of

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The results of these fits can be seen in **Error! Reference source not found.**c and Figure 4-3d. The agreement of this form is better than 0.1% throughout the whole wavelength range and the determined tuning curve is

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where is in nanometers and is in megahertz. Note that this relationship is temperature dependent. However, even when considering the potential temperature changes during the balloon flight, this would impact the relation by maximum wavelength drift of 2.5 nm. This level of uncertainty has a very small impact on the aerosol retrieval due to the slowly varying scattering cross section and it was decided that this relationship would not be actively changed with temperature. Furthermore, it should be noted that even though the AOTF optical range is 600 nm to 1200 nm, our analysis only measured wavelengths from 600 nm to 1080 nm due to the low quantum efficiency of the CCD beyond this range.

## 4.3.2 Point Spread Function

The spectral Point Spread Function (PSF) of the AOTF was also determined using the same set of data that was used for the tuning curve calibration. The spectral PSF was found by determining the FWHM for each wavelength. These results are shown in Figure 4-3b. The sidelobes in Figure 4-3a are a known AO effect discussed in section 3.2.2 as a result of Equation 3.17, and for the Brimrose AOTF this amounts to 8-14% of the total signal depending on wavelength. As noted in the previous section, the PSF of the AOTF and the spectrometer are convolved in this analysis. Even with this widening bias to the spectral PSF, the AOTF spectral resolution is well within the limits that are required in order to determine aerosol extinction in the upper troposphere and lower stratosphere (see section 2.6.1).

## 4.3.3 Diffraction Efficiency

An additional experiment was performed at several wavelengths to determine the RF power that yielded the highest optical throughput with the AOTF using a collimated light source. It was found that at all wavelengths the maximum throughput occurred when the RF power was at the recommended limit of 2 W. Following this, the diffraction efficiency of the AOTF was determined by using two sets measurements. The first is the experimental data used to perform the tuning curve analysis, and the second is a set of measurements of the intensity of the incident collimated light beam. The incident light in both measurement sets was linearly polarized and aligned with the polarization axis of the AOTF; to create the second set of measurements, the AOTF was simply removed from the optical chain. It should be noted that the attenuation of the AOTF crystal itself was not determined independently and is combined with the diffraction efficiency. As we are more concerned about signal throughput of the device a measurement of the combination of the effects is acceptable. The incident light source was then measured with the same iHR320 spectrometer and Synapse CCD with identical settings. By taking the ratio of the intensity at the diffracted wavelength to the incident intensity the diffraction efficiency was determined. It was found to vary between 54 and 64% across the measured spectral range. Equation 3.18 was not used to determine a theoretical diffraction efficiency due to the fact that some of AOTF parameters, such as interaction length, were unknown due to the proprietary nature of the device. However, our results agree with the experimental diffraction efficiencies supplied from Brimrose with the AOTF.

It should be noted that the diffraction efficiency changes also with respect to incoming angle and this experimental determination only measured the diffraction efficiency at normal incidence (*Xu and Stroud*, 1992). It is acceptable to only perform these measurements at normal incidence since the loss of signal is small as long as the incident angle remains within the acceptance angle of the device, which in this case is 2◦.

# 4.4 ALI Calibrations and System Test

A series of pre-flight laboratory calibrations were performed on the complete ALI instrument. The instrument was characterized as a complete system to provide calibrated radiance and estimate flight exposure times. The following pre-flight tests and calibration measurements were performed on ALI:

* Exposure time determination
* DC offset removal
* Dark current correction
* Stray light calibration
* Relative flat-fielding correction

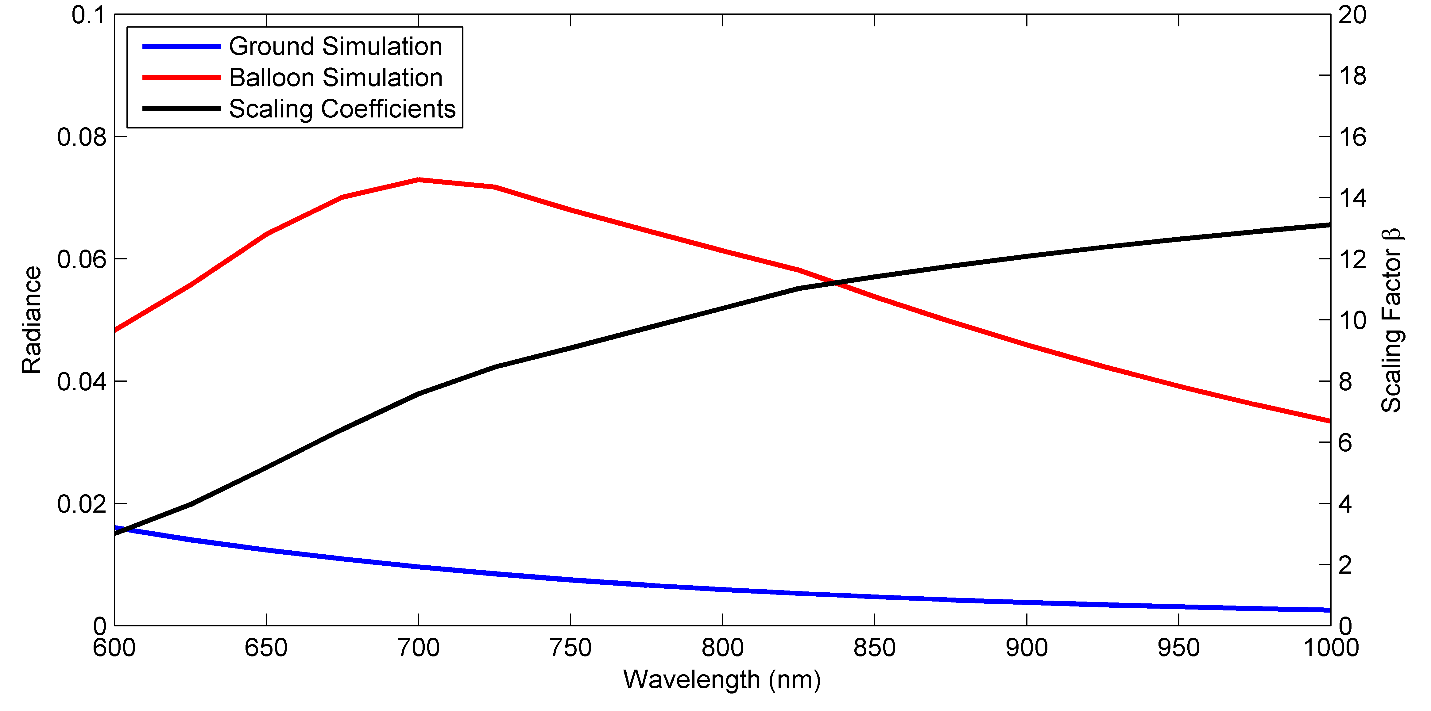
## 4.4.1 Exposure Time Determination

An experiment was performed to determine exposure times for the stratospheric balloon flight, as well as to verify the design of the entrance pupil size of the system. On July 12, 2014 from 13:00 to 16:00, during clear conditions, ALI was placed on the roof of the University of Saskatchewan Physics building (52.13◦N 106.63◦W) pointing approximately 90◦ in the azimuth direction from the sun, and measurements were recorded with a range of exposure times (0.01 to 120 seconds) and wavelengths (600 to 1000 nm). These ground based measurements were then used to determine the exposure times that would be required when imaging the atmospheric limb from the float altitude of the stratospheric balloon.

The SASKTRAN-HR radiative transfer model was used to determine the scaling factors that relate the ground-based radiance to the limb radiance. Using the scalar SASKTRAN-HR (*Bourassa et al*., 2008; *Zawada et al*., 2015) radiative transfer model, discussed in detail in section 2.4.5, radiance profiles were simulated from the ground-based geometry and a simulated balloon flight geometry. The simulated radiances for the ground based and balloon flight geometry are shown in **Error! Reference source not found.**. A scaling factor, , is determined based on the ratio of the ground based and balloon based geometries and is used to adjust the integration times. The scaling factor can be used in combination with the ground based determined integration times, in the following

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where is the integration time from the balloon platform, and and are the simulated scalar radiances from the balloon and ground, respectively. The scaling factor is shown in black in Figure 4-4 and the estimated balloon geometry exposure times are located in Table 4-2.



**Figure 4-4**: Simulated scalar radiances from the SASKTRAN-HR in blue and red with the radiance on the left side and the scaling factor in black with the value on the right side.

The exposure times determined were designed to be on the order of a second during the flight which was performed by selecting an appropriate entrance pupil size of 9.91 mm; however, a severe limitation in the measurement frequency capability of the instrument was the read-out speed of the CCD detector. This was very slow compared to the exposure times and on average took 20 second per image, which greatly reduced the measurement density. Nonetheless, with a faster detector read-out, the desired measurement density could be achieved. Approximate exposure times estimate for the balloon flight are listed in Table 4-2. Flexibility was maintained in the control software to adjust these with ease during the flight.

**Table 4-2:** Estimated balloon flight exposure times.

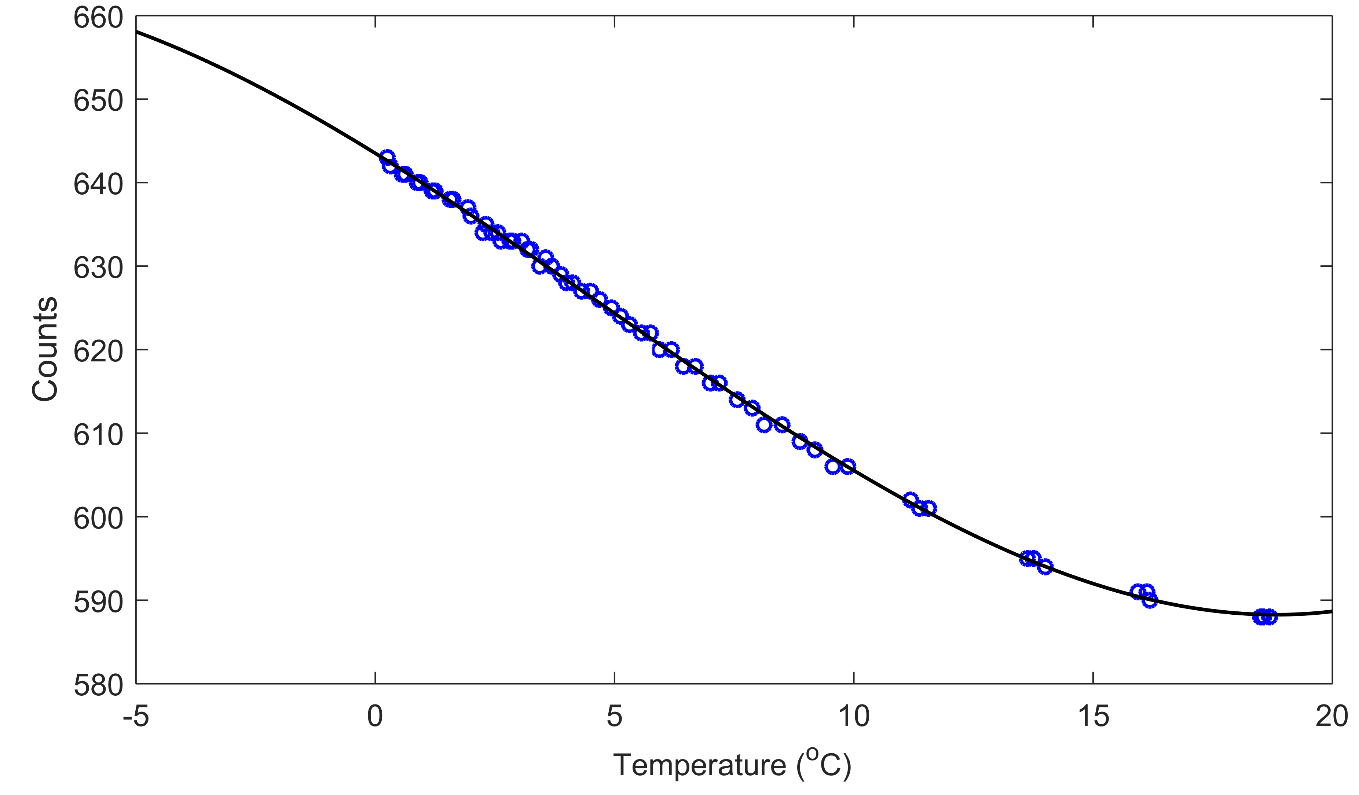
|  |  |
| --- | --- |
| Wavelength (nm) | Exposure Time (s) |
| 650 | 2.00 |
| 675 | 2.00 |
| 700 | 1.39 |
| 725 | 0.38 |
| 750 | 0.10 |
| 775 | 0.10 |
| 800 | 0.10 |
| 825 | 0.33 |
| 850 | 0.47 |
| 875 | 0.48 |
| 900 | 1.00 |
| 925 | 2.00 |
| 950 | 2.00 |

## 4.4.2 DC Offset Removal

The DC offset is a bias that is applied to the analogue to digital converter inside the CCD camera, which causes a bias in the final count values for the image and needs to be removed in order to be able to get the pure measurement counts due to photons. It is usually assumed that the DC offset for a CCD is a constant across the operating temperatures and exposure times of the device; however, the DC offset for the camera used in ALI exhibited a temperature dependence. Dark images were acquired in the laboratory to be used in the calibration. Additionally, a calibration mode was used on the ascent of the balloon during the campaign that acquired dark images which were used to further calibrate the DC offset. All of the dark images were taken with the shortest possible exposure time of 0.01 s to reduce any dark current contribution from the images. The mean value of the counts for each image was determined and was used to determine the DC offset. The standard deviation of the counts for each image ended up being approximately 2% of the average value. Using this data, a curve was fit to determine the DC offset with respect to temperature. The curve is in the form of

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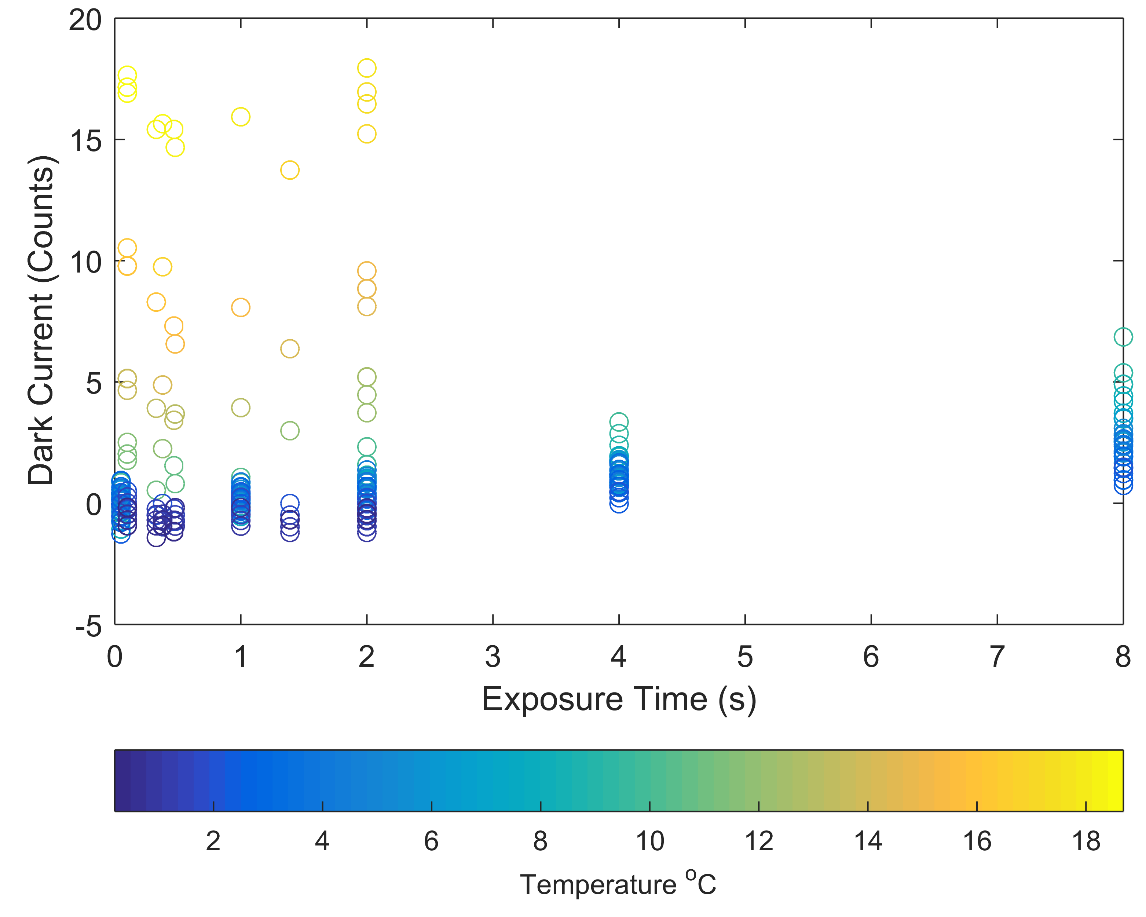
where is the temperature of the detector in degrees Celsius to determine the offset that needed to be removed and is plotted in Figure 4-5.



**Figure 4-5**: The DC offset curve (Equation 4.5) is seen in black where the lab and flight calibration data is shown in blue. The counts on the vertical axis are the counts that need to be removed to account for the DC offset.

## 4.4.3 Dark Current Correction

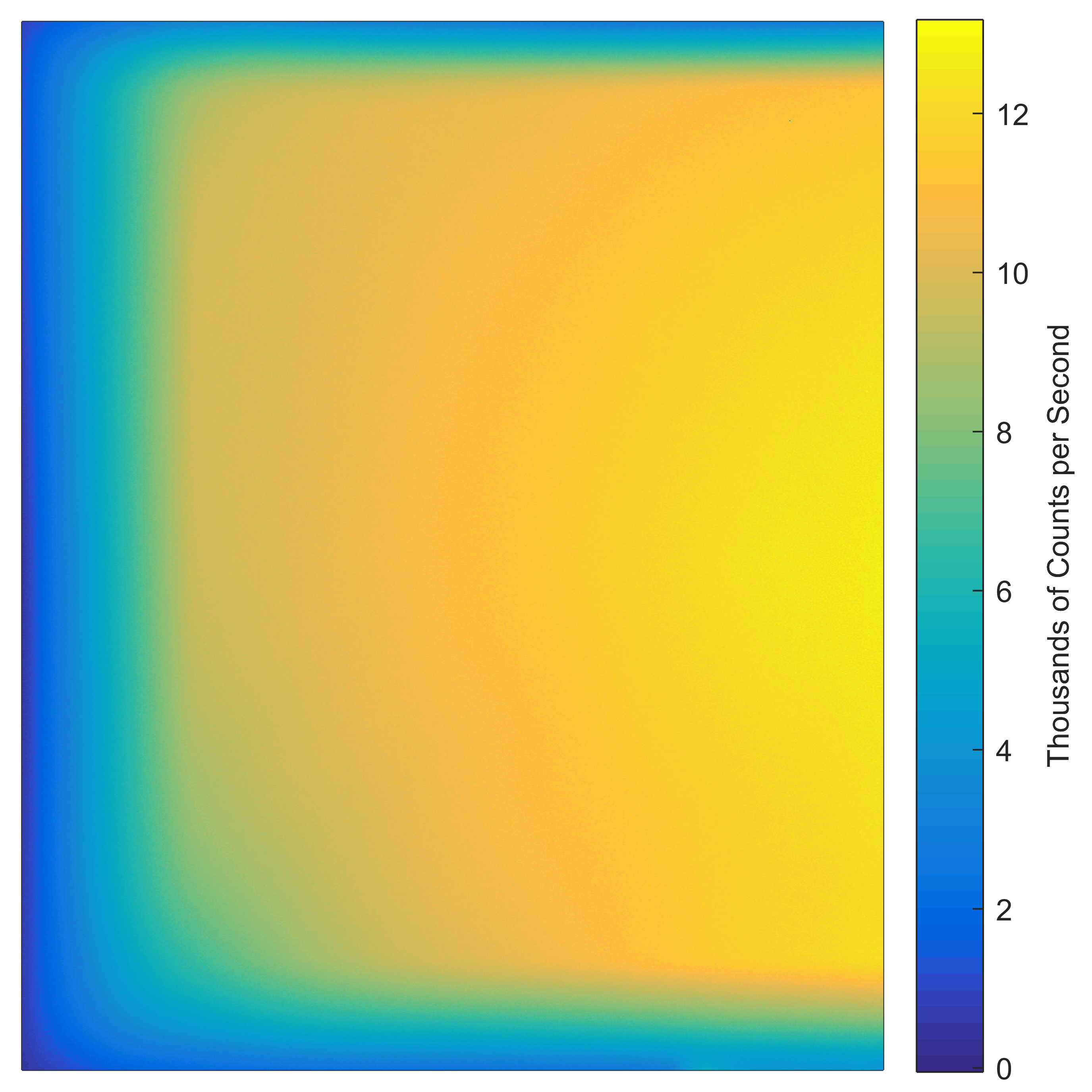
The dark current is due to thermally generated electron-hole pairs, and grows linearly with exposure time and nonlinearly with temperature. By using images taken in darkness with a variety of exposures time, the dark current can be determined by looking at the residual after the DC offset has been removed using the curve developed in the previous section. The residual of the counts for the calibration dark image can be seen in Figure 4-6. During the campaign, the operating temperature of the camera was less than 10◦C throughout the entire flight and most exposure times were less than five seconds leaving a very small dark current contribution in the measurement images, at worst approximately seven counts. This level of dark current was small compared to the other signal levels and was simply considered an additional noise term in the error analysis.



**Figure 4-6**: The dark current from the calibration images over a series of camera temperatures and exposure times.

## 4.4.4 Stray Light Calibration

A laboratory experiment to characterize the stray light in the ALI system was performed. Two types of stray light exist; the first is out-of-field stray light, *i.e.* signal that enters the optical path that originates outside of the FOV. The second is internal stray light, which is caused by scattering, reflections or other imperfections in the optical elements. As mentioned previously, stray light removal is critical for limb scatter measurements.



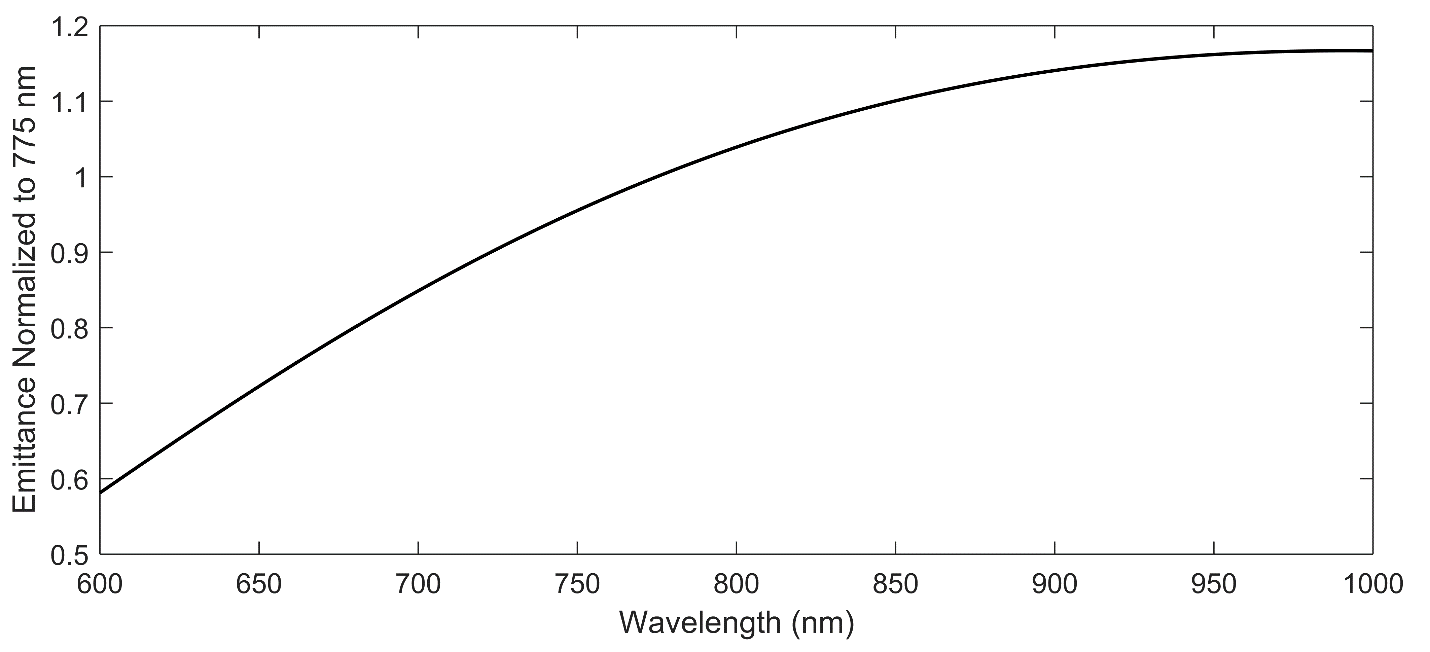
**Figure 4-7**: A calibration image after stray light removal has been performed where the measured wavelength is 750 nm with a 1 second exposure time. Vignetting can be seen as moving away from center of the image. Additionally the last 1◦ of the horizontal FOV is on the right side is lost due to strong contamination from reflections within the system. Originally published as Figure 7 in *Elash et al.* (2016).

The use of the AOTF has potential to increase the amount of internal stray light due to the fact that the undiffracted beam and the unmeasured polarization also propagate through the system. However, the diffraction interaction only occurs when the acoustic wave signal is applied, so without the acoustic wave the recorded measurement only contains the stray light in the system. Using this unique characteristic of the AOTF, the stray light of the system was measured in the laboratory. A 250 W quartz-tungsten light source was passed through a dispersing screen and onto the entrance aperture of ALI, effectively filling the entire aperture and all angles within the FOV. Using a variety of exposure times, ranging from 0.1 to 60 s and wavelengths from 650 to 950 nm in 25 nm intervals, this diffuse source was imaged twice, once with the AOTF in its off state, with no driving acoustic wave, and once with the AOTF in its on state, with the acoustic wave applied. For each pair of measurements the image with the “AOTF-off” only contains stray light in the system, and the “AOTF-on” image contains the stray light combined with the image of the diffuse source. Subtracting the “AOTF-off” image from the “AOTF-on” image yields a final image that contains only the image of the diffuse source. A typical example of a resulting image is shown in Figure **4-7**. The observed vignetting is caused by the aperture of the AOTF, expected from the ray tracing model, and light entering the AOTF outside the acceptance angle. Note that this method also partially removes dark current associated with the detector. This two-image method was used operationally during the balloon measurement campaign such that images captured had a corresponding “AOTF-off” image immediately obtained with the same exposure time. For the calibration images an average stray light to signal ratio of 2.5·10-2 was noted.

## 4.4.5 Relative Flat-Fielding Correction

With the simple optical layout chosen for the prototype, some in-field light gets blocked by the AOTF aperture causing a vignetting of the image. As the FOV is increased, so is the vignetting. Furthermore, at the extreme range of the FOV, approximately the last half degree in each direction, the angles are outside the acceptance angle of the AOTF. This causes a decrease in diffraction efficiency. Both of these effects also need to be calibrated. The flat-field calibration corrects optical and detector level differences in the system across the FOV such that a calibrated image of a perfectly diffuse source yields a constant value across the image. The resulting images from the diffuse source described above were used to determine the flat fielding corrections for ALI. These were determined in two steps: spatial and spectral.

The experimental measurements from the stray light calibration mentioned above were also used to perform the relative flat-fielding calibration. For the spatial correction the stray light as removed and for each image at a given wavelength, each pixel was scaled to the mean value of the center 25x25 pixels. These scaling factors were averaged across all images of the same wavelength to determine the flat-fielding coefficient for each wavelength. The flat-fielding scaling coefficient had no more than a 4% standard deviation.

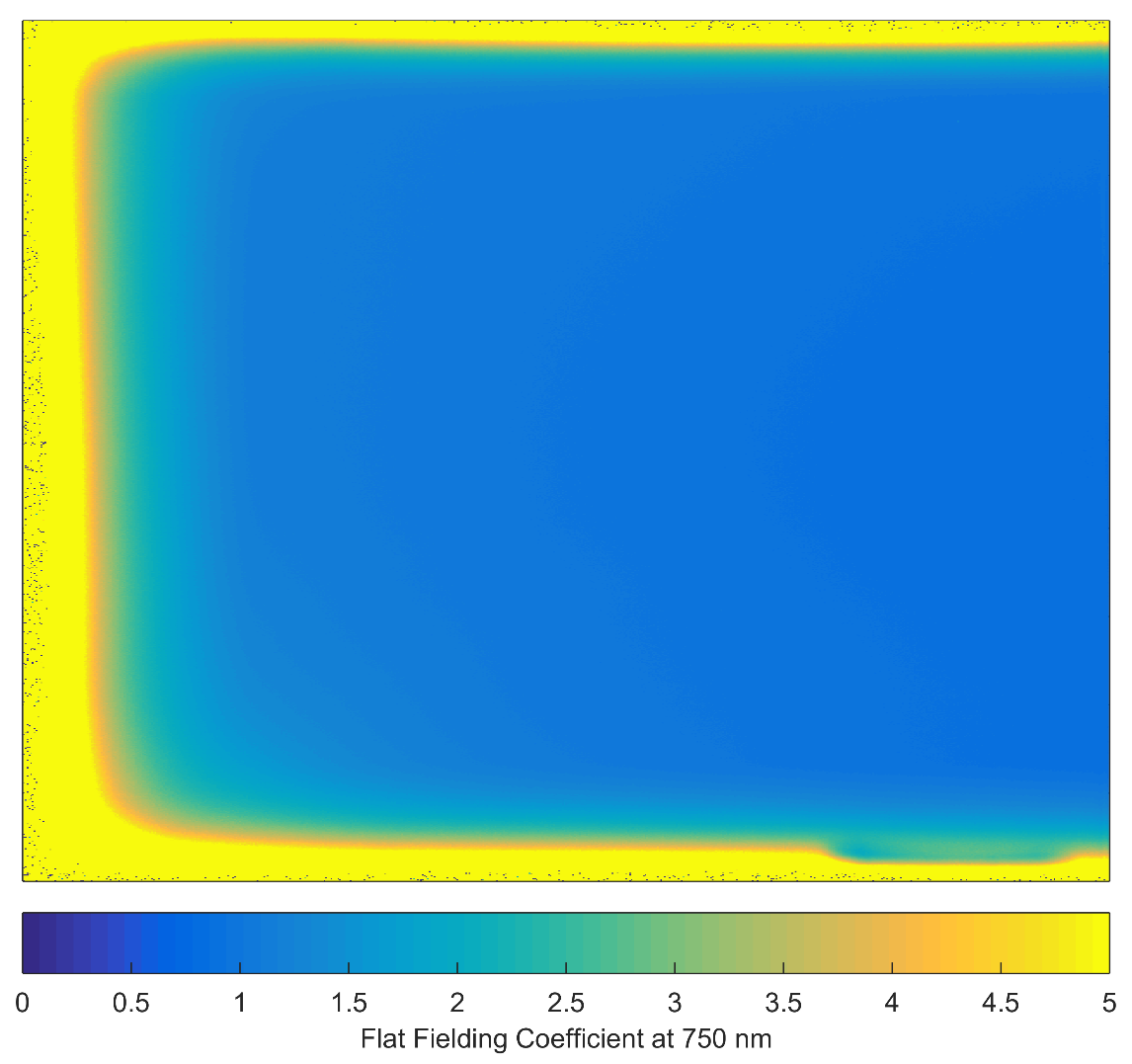


**Figure 4-8**: The blackbody emittance curve from Equation 4.6 normalized to 775 nm.

For the spectral calibration, ALI is most sensitive at 775 nm so this wavelength was chosen as the reference wavelength of a relative spectral calibration. All flat-fielding corrections were then scaled to the blackbody curve of a tungsten halogen bulb normalized to 775 nm assuming an operating temperature, , of 3300 K using a method by *Kosch et al.* (2003). The blackbody emittance, , of a filament bulb is given by

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where is the emissivity of the tungsten filament, is the speed of light, is Planck’s constant, and is Boltzmann’s constant. The emissivity values for tungsten were acquired by work done by *Forsythe and Worthing* (1925) and used to compute the spectral emittance of the bulb normalized to 775 nm seen in Figure 4-8.



**Figure 4-9**: The flat fielding coefficients for 750 nm.

An example of the flat fielding coefficients for 750 nm can be seen in Figure 4-9. A majority of the coefficients for the central FOV are near unity, yielding good sensitivity throughout most of the image. However, due to the vignetting and the loss of diffraction efficiency near the edges of the image, the flat fielding values in these regions are larger than the more central FOVs. Note that no absolute calibration was performed due to lack of availability of an appropriately calibrated source.

# 4.5 Integrated Testing

With the completion of the ALI instrument, including the optical chain, power and electronics hardware, and system software, a full system test was performed, including a mass and power check. ALI was set up in a flight configuration to simulate the launch of the balloon. During the test, ALI was completely controlled from a ground station computer over a local area network to simulate the stratospheric balloon’s communication interface. All commands were sent to ALI from the ground station and the simulation performed a full but shortened mission plan, which including pre-flight checks, launch, science measurement acquisition, and mission termination. During the simulation, the temperature and pressure during the flight could not be simulated. However the electronics were pressure tested separately and no issues were noted.

The full integration testing occurred on August 18, 2014, along with a second instrument, the OSIRIS development model (*Kozun* 2015; *Taylor*, 2015) which was flown alongside ALI during the Timmins campaign. The OSIRIS development model was connected to the same local network, as would be the case during the flight, to be a further test for both ALI and OSIRIS to locate any cross communication problems between multiple instruments.

The testing suite for ALI consisted of testing the pre-flight commands to verify full systems operation, ascent operational mode, science operational mode, and system power down. Each mode tested the various states of ALI during the balloon mission. Further, all of the possible commands for ALI were also tested in various orders to verify no issues with their operation.

The full integration test found a few minor software bugs that were not found prior, but no major problems were noted with ALI itself or any cross communication problems with the OSIRIS development model. The minor software issues were patched and tested on ALI before a final stable version of the software was loaded onto both the ground and flight computer systems and were considered to be the final flight version for the mission. Finally ALI’s power consumption and mass were checked to verify that they were within the requirements as listed in section 2.6.1. The total mass was 37.4 kg ± 5% and the average power draw was 70 W ± 10% with a peak draw of 80 W ± 10%, which are within the requirements of the balloon flight.

1. Portion of sections 4.3.1, 4.3.2, 4.3.3, 4.4.4 and 4.4.5 as well as **Error! Reference source not found.**, and Figure **4-7** were originally published in *Elash et al.* (2016) [↑](#footnote-ref-1)