CHAPTER 4

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

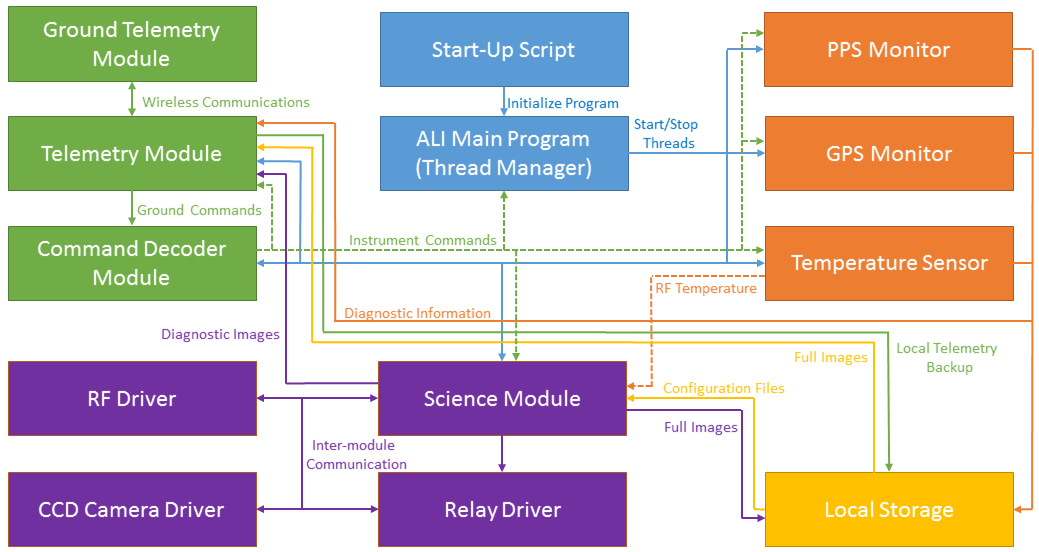
# 4.1 Introduction

A finalized ALI instrument has been developed and constructed through careful considerations of optical and opto-mechanic concerns. The special requirements of the AOTF and balloon platform were met within the design of the system. However, the completed system required calibration and testing to achieve high quality measurements. Additionally, control software to operate the system from the balloon platform is required. This chapter focuses on discussion of the control software written for ALI and following are the calibrations preformed to achieve high quality radiance measurements. For the calibration experiments the AOTF used in ALI is characterized followed by the calibration of the entire system. Finally, a fully integrated test of the ALI system is underwent as a final test before the stratospheric balloon flight in Timmins, Ontario.

# 4.2 Control Software

During the stratospheric balloon flight, software is required in order to control the instrument from the ground and have it operate in the air. Two separate software packages were developed to accomplish the communication and control systems required for the mission. First, a ground control platform that communicated to ALI which received diagnostic information, completed images, and sent commands to be processed. The second software package was the onboard system that controls the instrument systems.

The ground control software contains the module that 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 software onboard ALI is more complicated with different modules to handle the different aspects of the hardware and control systems. The onboard ALI computer system is a Debian Linux operating system with multi-threaded C++ based software that controls the hardware and science data collection operation. The onboard computer is a VersaLogic PC-104 OCELOT computer with fanless operation and a thermal operating range of -40 to 85◦C. The 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 will follow.



**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 device used for the gondola's communications and telemetry system) every second. It is a constant signal between all instruments on board to correlate each systems data to each other. The voltage sensors verify 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.

|  |  |
| --- | --- |
| 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, the QSI CCD camera, and the RF driver. 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 in an operational mode as specified from the ground. The science mode controls all of the hardware and process the imaging cycle and 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 that contains the required information to verify the success of the flight operations and instrument in case the local solid state data is not recoverable after the balloon flight. When the mode is completed the same modes are repeated unless ALI 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. There are two reasons to include diagnostic images. First, having diagnostics on every image gives the users real time information if the measured data is saturated or under exposed and adjustments can be made during the mission. The second reason is there is no guarantee that when the gondola lands ALI will survive. The balloon can land in water or crash land destroying the stored data. In case of such events, some data is sent down for every image so analysis and results can still be acquired from the ALI mission and can be used to verify the feasibility of the technology. Lastly, any extra bandwidth that is not allocated to other processes is used to transmit complete images down to the ground for complete horizontal and vertical verifications of the ALI instrument.

# 4.3 AOTF Calibration

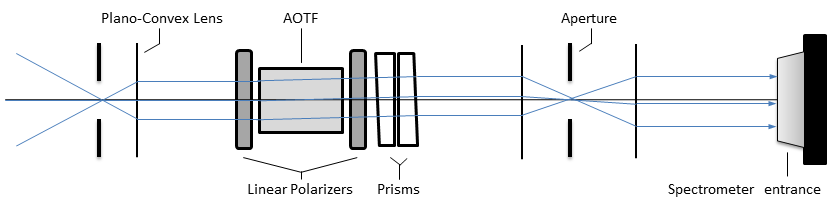
The calibration of the AOTF is performed within this this section. The AOTF is from Brimrose of America and the specifications can be found in appendix A.1.3. The AOTF needed to be fully calibrated to expand upon the factory specifications to be able to accurately use the AOTF within the ALI system. The calibrations preformed on the AOTF are:

* A tuning curve analysis
* A point spread function analysis
* Diffraction efficiency determination.

## 4.3.1 Tuning Curve Analysis

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

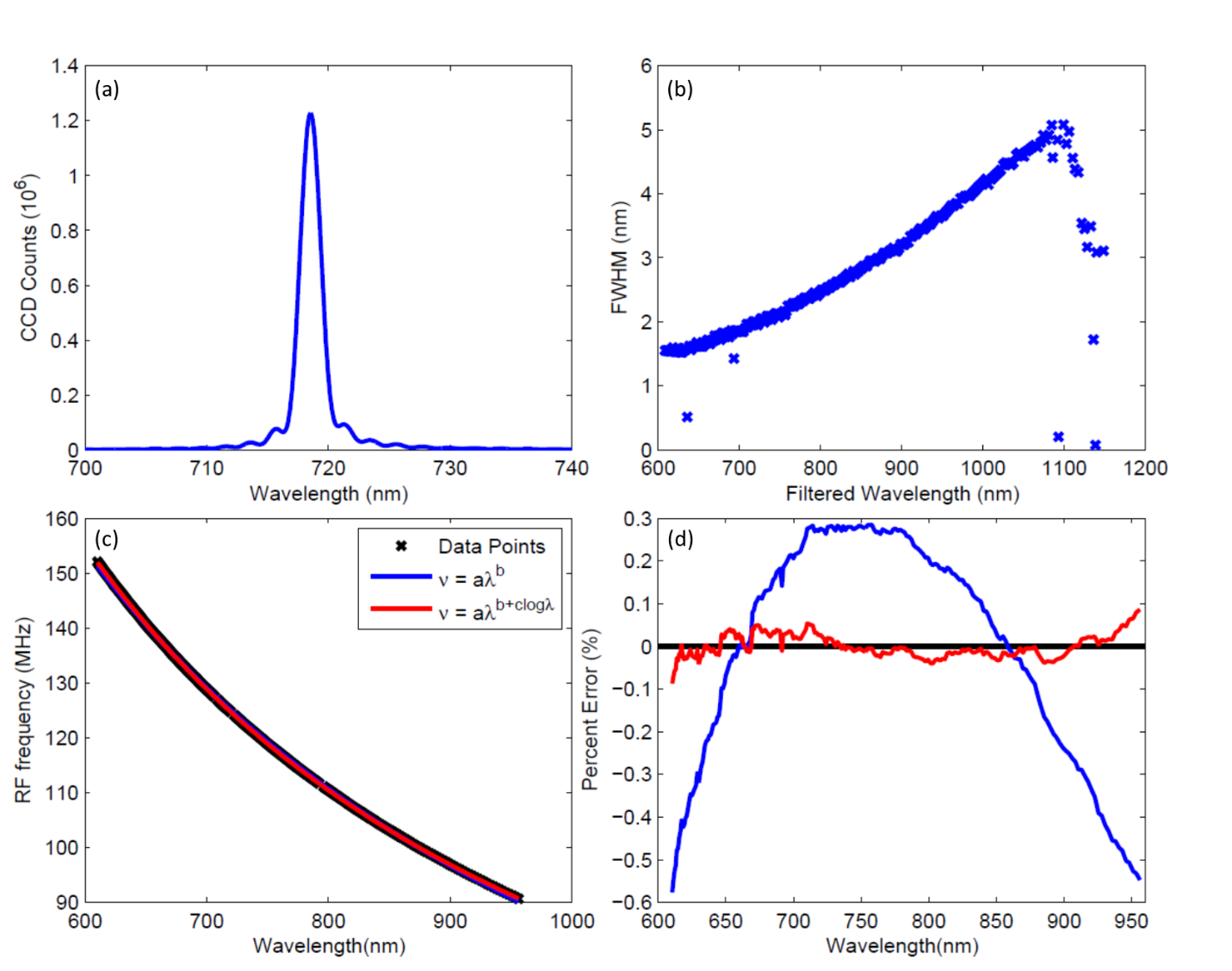
For this analysis, a telecentric test layout was used, the details of which are described in section 3.3.2. An advantage of the telecentric testing layout is that the wavelength dependence of the acousto effect from the incident angle, noted in Equation 3.32, is removed since all the lines of sight enter 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 unwanted polarizations. 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. It also enabled the system to have 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 Synopse 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 with a normal distribution, which is less than the minimum factory specified resolution of 1.6 nm. The final recorded spectra would be a convolution of the PSF of the AOTF and spectrometer, however this will have a small effect on the determined spectral resolutions by making them appear to be slightly larger than the AOTF itself, but with the broadband nature of aerosol scattering this is not a large concern since the true PSF will be better than that measured. At each RF two images were taken with a 15 second integration time: one with the AOTF in its on state and another with the AOTF in its off state. The stray light, dark current, and the DC bias are recorded in the image with the AOTF off and can be removed from the AOTF spectral image by taking the image with the AOTF on and subtracting the image with the AOTF off. 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 and the corresponding wavelengths. The tuning curve from section 3.2.4 (Equation 3.32) was not used since some of the AOTF parameters were not known and an imperial fit was used instead. It was noted that the curve appear to follow a power function of the form

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|  | (4.1) |

A linear least squares fit was performed in log space finding the coefficients and . The fit was performed and appeared to match the data quite well but a relative error analysis was preformed and it was seen that there was only an agreement better than 0.6% near the edges. 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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|  | (4.3) |

where is in nanometers and is in megahertz with a 0.1% error in the central wavelength. Additionally the AOTF will undergo temperature changes during the flight. However, even when considering the temperature changes during the balloon flight, the AOTF would experience a maximum wavelength drift of 2.5 nm during the mission which is acceptable for the slowly varying broadband scattering of aerosol. 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 from the induced RF wave and for the Brimrose AOTF amounts to 8 to 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 experiment was performed on several wavelengths to determine the RF power that yielded the highest throughput through the AOTF using a collimated light source. For the AOTF in ALI, the maximum throughput occurred when the RF power was at the recommended limit of the AOTF, which was 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 wavelength calibration, and the second is measurements of the intensity of the incident collimated light beam. The light in both experiments was linearly polarized and aligned with the polarization axis of the AOTF; for the second set 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. We are more concerned about signal throughput of the device so 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 unknown AOTF parameters such as interaction length. 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 measurement normal incidence since the loss of signal is small as long as the incident angle remains within a certain range known as the acceptance angle. For the AOTF used in ALI the acceptance is 2◦.

# 4.4 ALI Calibrations and System Test

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

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

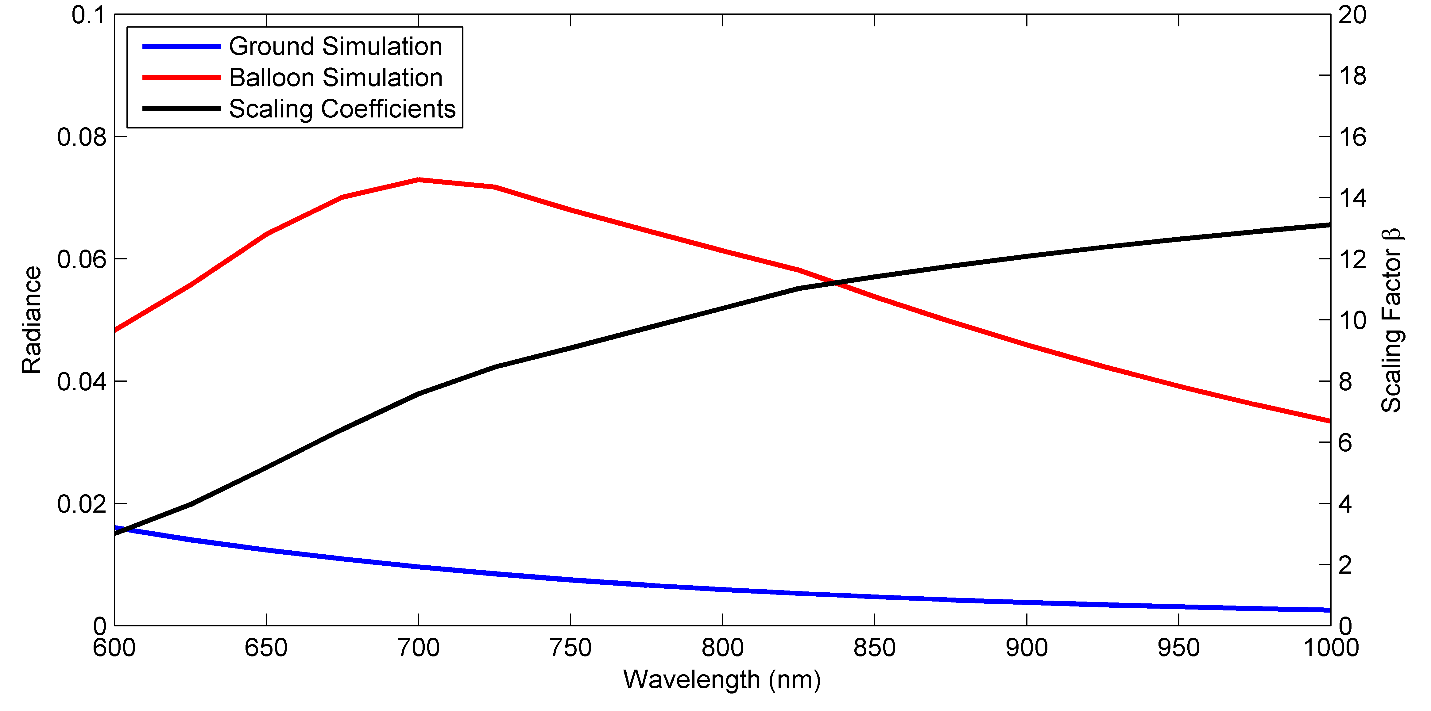
## 4.4.1 Exposure Time Determination

An experiment for ALI was performed to determine exposure times for the stratospheric balloon flight as well as 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 a building (52.13◦N 106.63◦W) pointing approximately 90◦ in the azimuth from sun and measurements were recorded with variety of exposure time (0.01 to 120 seconds) and wavelengths (600 to 1000 nm). The exposure times that would achieve a three quarter full well on the ground were determined for each wavelength. However, the exposure times were needed for the balloon geometry, not on the ground, where the change in altitude greatly changes the spectral radiance which alters the exposure times.

To address this issue a radiative transfer model is needed. A radiative transfer model has been developed at the University of Saskatchewan over the past 15 years. 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 a ground-based geometry and a simulated balloon flight geometry. The simulated radiance profiles for the ground based and balloon flight geometry are seen in **Error! Reference source not found.**. A scaling factor, , is 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 can be observed 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, there was some uncertainty with the exposure times determined. The radiances used from the SASKTRAN-HR model were scalar since the vector model was still in development. ALI is a polarized instrument so the effect polarization would have on the scaling factors was unknown. To account for the unknown effect from the lack of simulated polarized radiances, the software was designed to be able to change the exposure time curve during the mission as required. Finally the read out speed of the CCD camera was slow compared to the exposure times and on average took 20 second per image, which greatly reduced the measurement density.

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

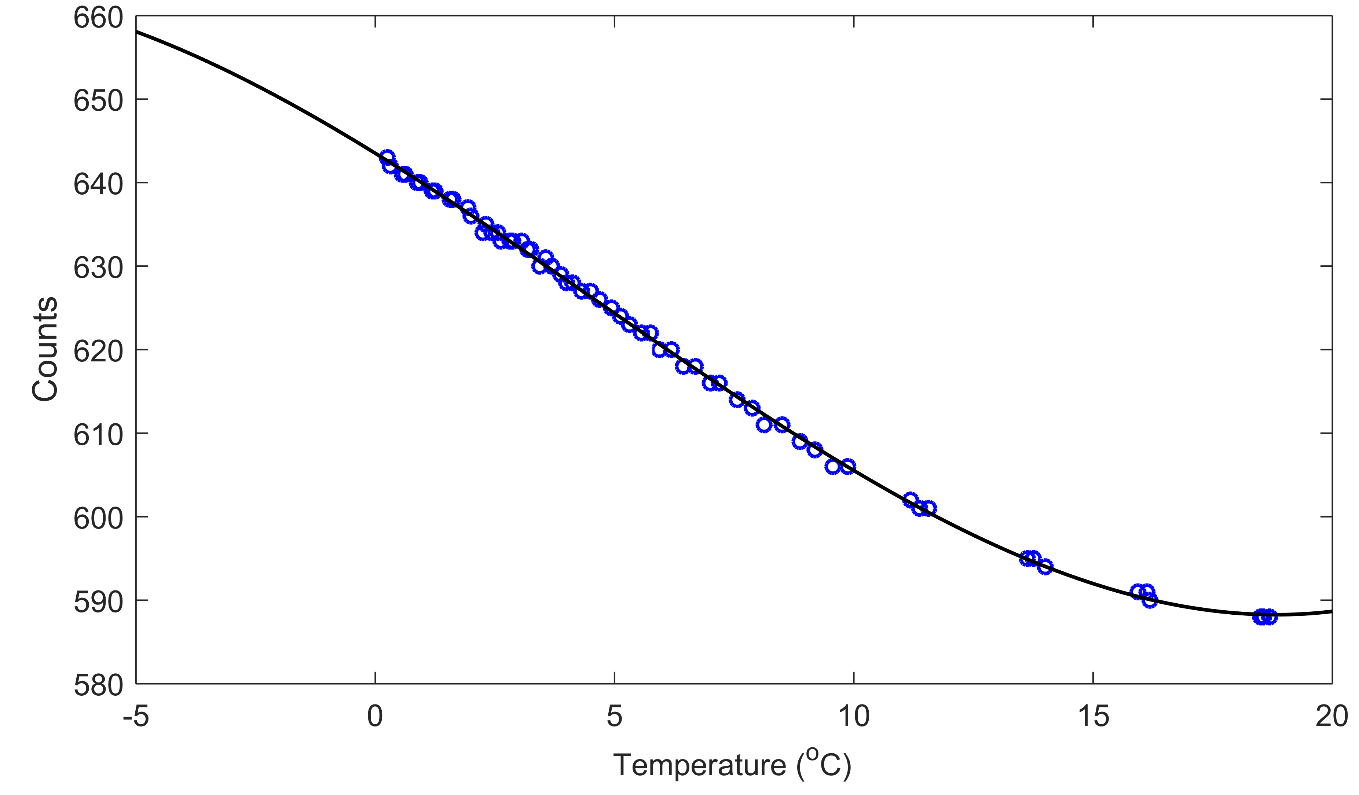
|  |  |
| --- | --- |
| Wavelength (nm) | Exposure Time (s) |
| 650 | 2.00 |
| 675 | 2.00 |
| 700 | 1.39 |
| 725 | 0.38 |
| 750 | 0.10 |
| 775 | 0.10 |
| 800 | 0.10 |
| 825 | 0.33 |
| 850 | 0.47 |
| 875 | 0.48 |
| 900 | 1.00 |
| 925 | 2.00 |
| 950 | 2.00 |

## 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 that 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 from the instrument. 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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|  | (4.5) |

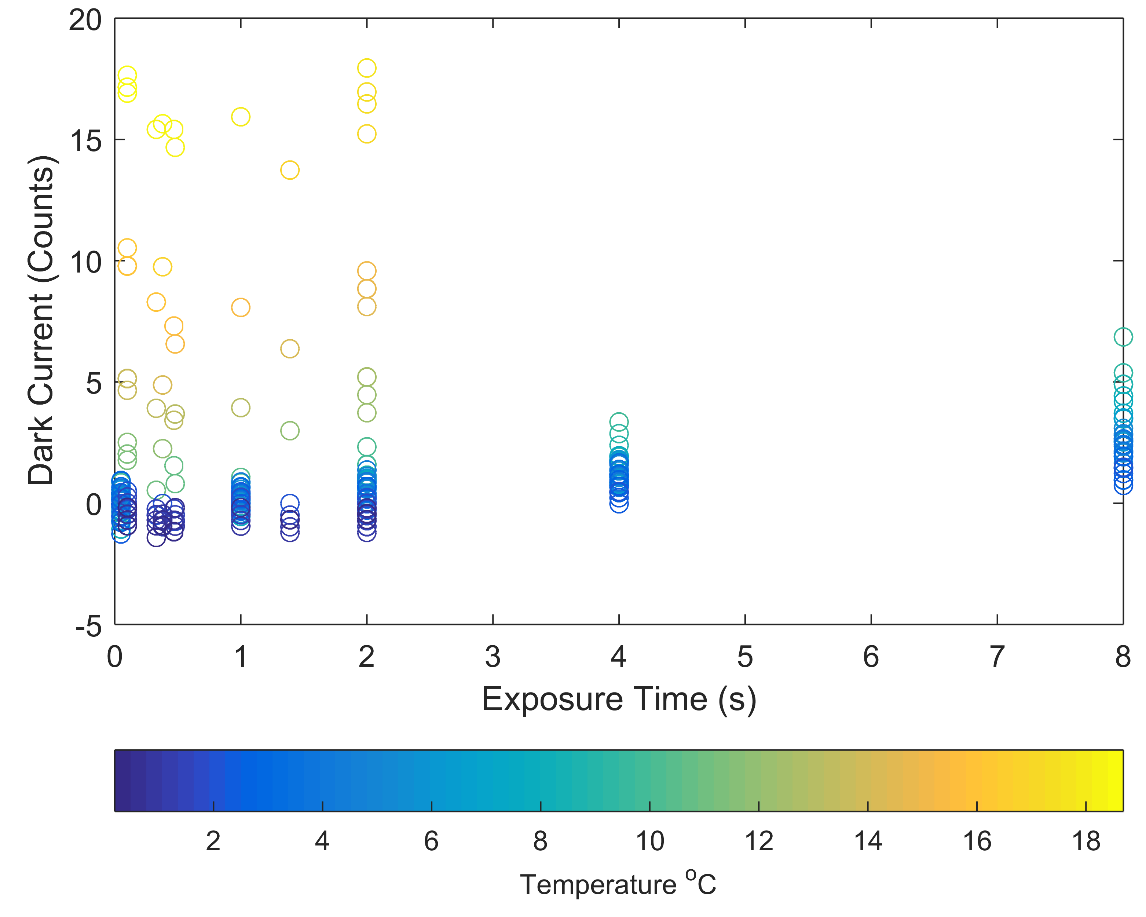
where is the temperature of the detector in degrees Celsius to determine the offset that needed to be removed and is plotted in Figure 4-5.



**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

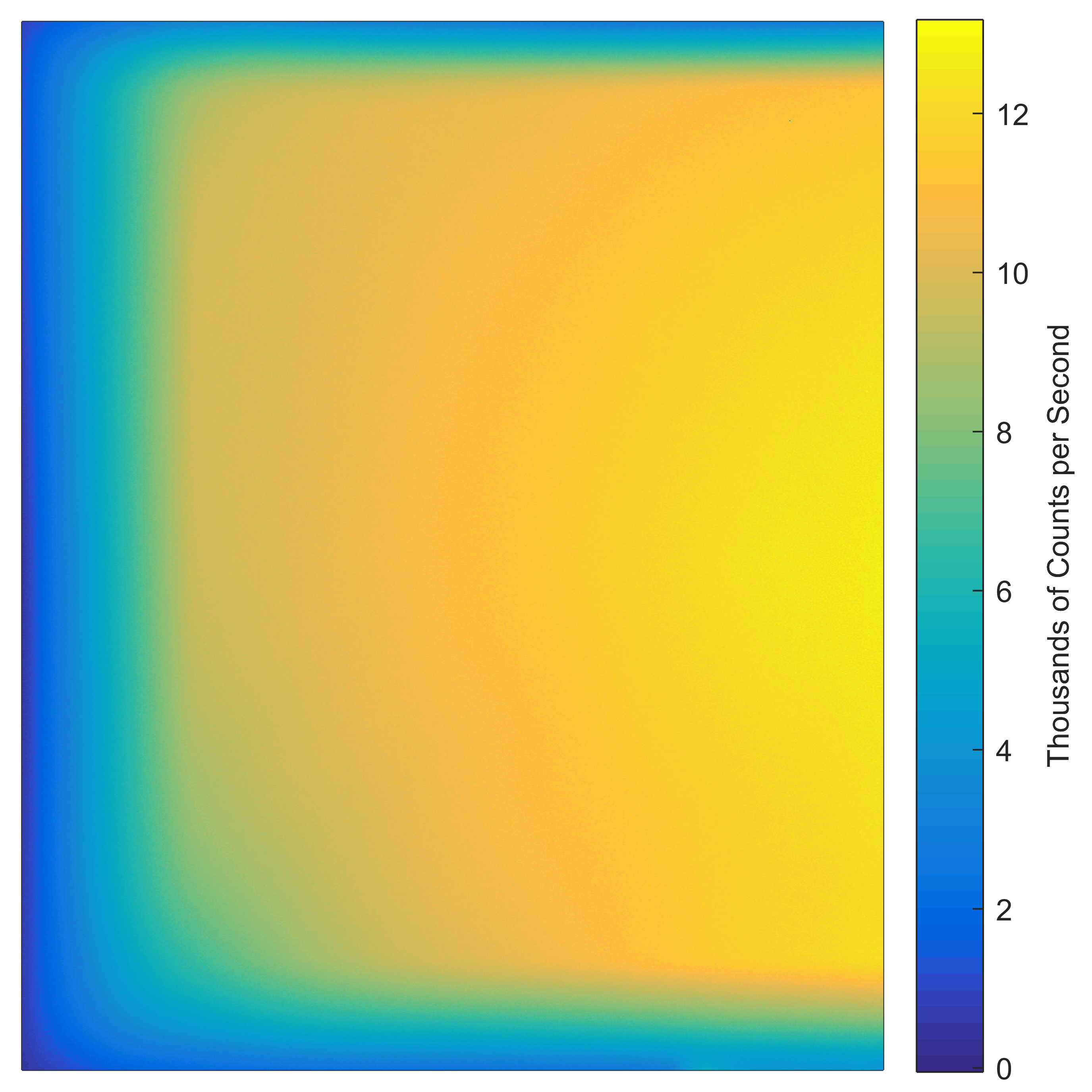
The dark current is thermal energy that builds up in the CCD detector. It grows linearly with exposure time and nonlinearly with temperature. By using images taken in darkness with a variety of exposures time, the dark current can be determined by looking at the residual after the DC offset has been 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 seven counts. The seven count dark current was small compared to the DC offset and was considered to be an addition noise source added to the error for the radiances. With the removal off the CCD artifacts of DC offset and dark current stray light additional system calibrations of stray light and relative flat fielding could be performed.



**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.



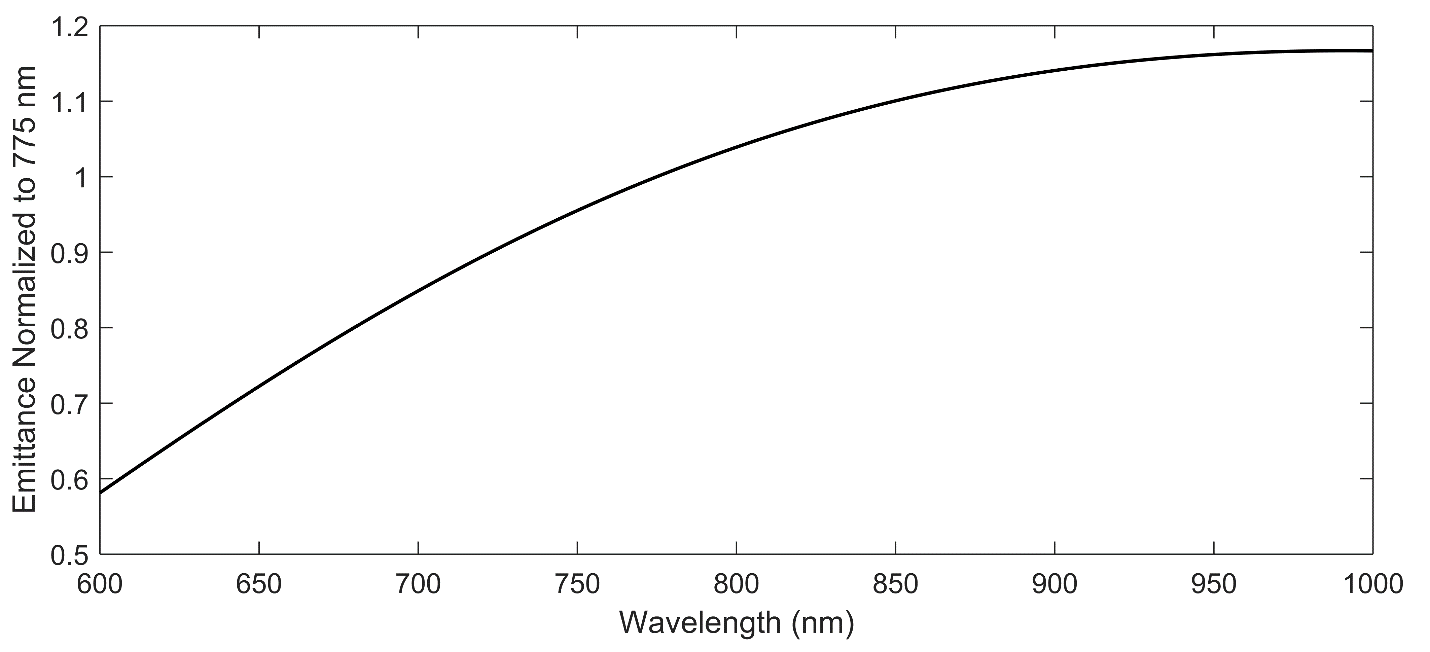
**Figure 4-7**: A calibration image after stray light removal has been performed where the measured wavelength is 750 nm with a 1 second exposure time. Vignetting can be seen as moving away from center of the image. Additionally the last 1◦ of the horizontal FOV is on the right side is lost due to strong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

By using a simple optical layout as chosen for the prototype, light gets blocked by the AOTF's aperture causing a vignetting on the images. As the FOV is increased, so is the vignetting. Furthermore, the extreme range of the FOV, approximately the last half degree in each direction, is outside the acceptance angle of the AOTF which causes a loss of diffraction efficiency. Both of these effects also need to be calibrated out of the measurements to achieve final radiances. 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 was also used to perform the relative flat-fielding calibration. For the spatial correction, for each image at a given wavelength, each pixel was scaled to the mean value of the center 25x25 pixels. A series of images was used to determine the mean flat fielding coefficient for each wavelength which had no more than a 4% standard deviation.

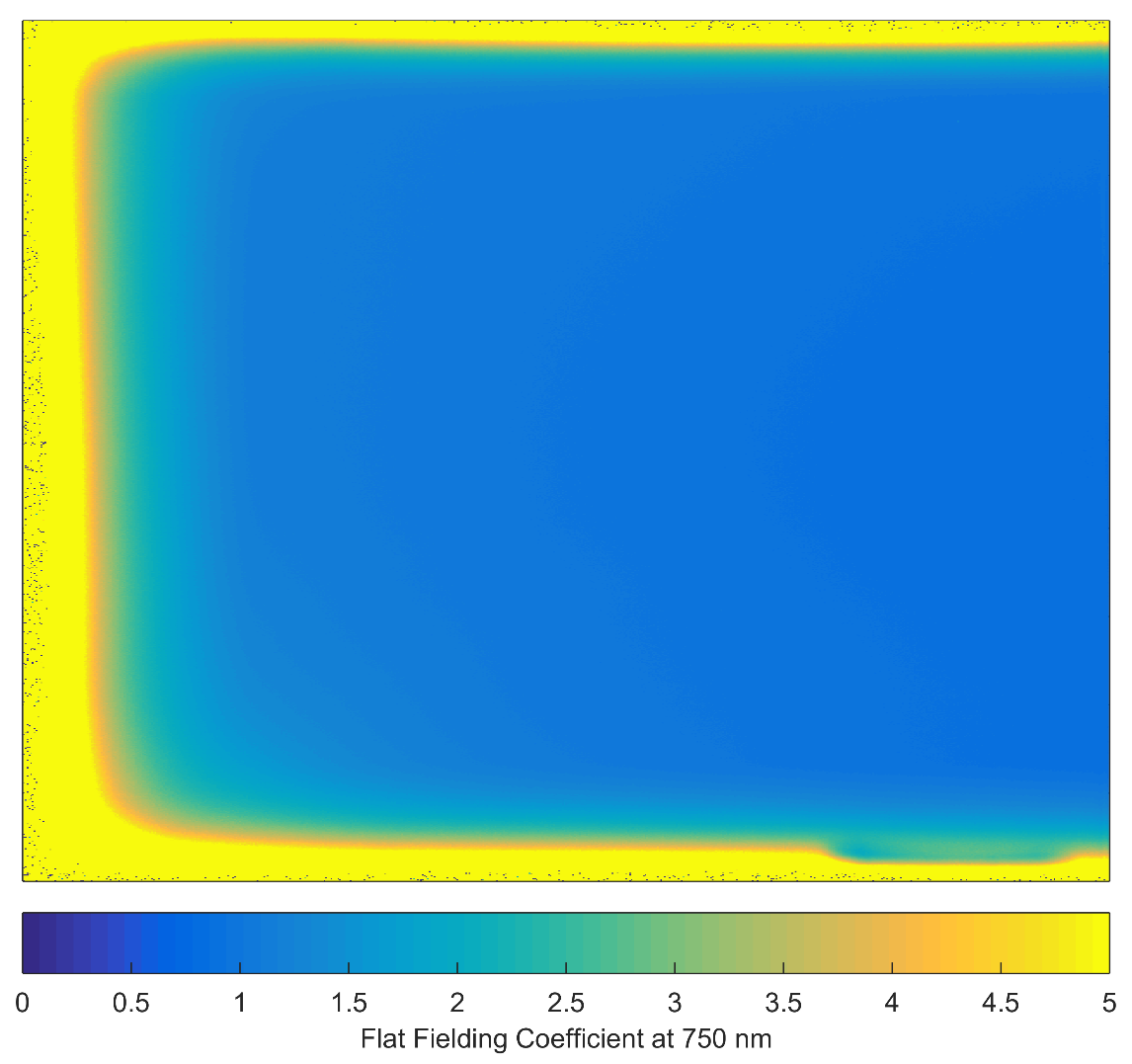


**Figure 4-8**: The blackbody emittance curve from Equation 4.6 normalized to 775 nm.

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 coefficient for the central FOVs are near unity which yield 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. It should be noted that the relative flat-fielding is the final calibration for ALI and the final radiances are relative to 775 nm. No absolute calibration was performed due to lack of availability of an appropriately calibrated source. For a future iteration of ALI, an absolute calibration would be strongly suggested to be performed.

# 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. All of the individual components of the system have been tested and verified but a complete integrated test was required to assure no undesired cross-communications occurs between ALI itself and other instruments. 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 specification of the mission.

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)