CHAPTER 3

OPTICAL DESIGN AND CALIBRATIONS[[1]](#footnote-1)

This chapter discusses the ALI instrument from the initial planning to the completed system, including calibration and laboratory testing. First, a discussion of the Acousto-Optical Tunable Filter (AOTF) is presented that covers the solution of the wave equation, diffraction efficiency, output diffracted angle, and tuning curve. These are used to develop the complete characterization and calibration of the specific AOTF used in ALI. Following is a discussion of the trade-offs of the two primary optical design layouts considered for the instrument. Then the final optical specifications of the chosen design are presented along with the opto-mechanical aspects of the instrument and the control systems required to support the ALI stratospheric balloon test flight. Lastly, the calibration of the ALI instrument and results from a full system test are presented.

# 3.1 AOTF Theory and Background

The fundamental piece of technology used in the ALI design is an AOTF, which provides tunable narrow band filtering of an incident optical signal with fast response times and no moving parts. The use of AOTF technology for space based initiatives is only recently possible due to the recent advances in creating AOTFs with the ability to maintain imaging quality performance over a wide acceptance angles. This section discusses the theory behind the AOTF.

## 3.1.1 Solution to the Acoustic Equation

An AOTF is a device that through phonon-phonon interaction and a Bragg-like diffraction process allows a broadband light source to be filtered and the output can be captured as an image. Two primary types of AOTFs exist, collinear (*i.e.* the acoustic wave is aligned with the incident beam, (*Harris and Wallace*, 1969)) and non-collinear (*i.e.* the acoustic wave and the optical beam do not propagate collinearly in the crystal, (*Chang*, 1977)) configurations, and both use an optically anisotropic medium (*Saito and Yano*, 1976). An anisotropic medium is a material that is transparent and has a different index of refraction based upon the polarization state of the incoming light and its propagation direction, commonly called birefringence. For imaging purposes, a wide aperture is required and such AOTFs have been developed (*Gass and Sambles*, 1991) and are currently readily available.

To effectively utilize to AOTF in a precision optical instrument, it is imperative to understand the detailed principle of operation. The AOTF undergoes a phenomena known as an Acousto-Optic (AO) effect which describes the interaction between sound and light waves within the medium, generally a crystal. The AOTF used in this work operates in the Bragg-like diffraction regime which will be assumed for this derivation. Understanding the interactions between the light and the sound (acousto) waves within the crystal leads to an understanding of the functionality of the device. For an AO interaction within the AOTF there are three fundamental signals, the first two are light waves that represented by an incident and diffracted (or filtered) electric fields and the third is a sound wave that is the applied RF wave. Solving the AO wave solution for an AOTF will determine the form of the incident and diffracted waves in terms of optical and medium parameters that are useful for determine primary characters of the operation of the device such as diffraction efficiency and wavelength calibration. The RF wave exerts a stress on the crystal within the AOTF and this stress is the basis to solve the AO wave equation.

The derivation will start with the determination of the AO wave equation starting form Maxwell’s equations. Amperes law and Faradays law are the foundation for the wave equation and are presented as

|  |  |
| --- | --- |
|  | (3.1) |
|  | (3.2) |

where is an electric field, is an magnetic field, is the current density, is the permeability, and is the permittivity. By taking the curl of the Equation 3.1, combining it with Equation 3.2, and assuming that the AOTF crystal is non-conductive (*i.e.* ) along with the identity and assuming the crystal has no net charge (*i.e.* ) gives the simplified wave equation in the form

|  |  |
| --- | --- |
|  | (3.3) |

The RF or sound wave creates a stress wave within the crystal that causes a modulation within the crystal effecting the dielectric permittivity. Since the dielectric permittivity is not a constant with time it induces a susceptibility yielding the following form

|  |  |
| --- | --- |
|  | (3.4) |

where is the induced polarization due to the stress in the AO medium given by and the change is the susceptibility, . It is important to note that if the input electric field is linearly polarized (*i.e.* ordinary polarization) then the stimulated electric field has a different linear polarization state (*i.e.* extraordinary polarization) (*Voloshinov*, 1996). It is standard to define the input electric field as the incident field and output electric field as the diffracted field. Remembering that the crystal is birefringent the indices of refraction for the two wave fronts will have differing indices of refraction. Using this standard the susceptibility where and are the indices of refraction for the incident and diffracted electric fields and is the elasto-optic coefficient which is dependent on medium and orientation of the crystal used and is the strain wave induced by the acousto wave. As mentioned earlier a solution for this equation is presented in the Bragg region meaning there will only be first order diffraction effects.



**Figure 3-1**: Geometry for the AOTF wave derivation assuming the acousto wave is along the x-axis and the AO interaction occurs along the z axis over a interaction length, . The parameters , , and are the position vector, wave vector, and angle of the incident electric field and similarly for the diffracted electric field. Figure recreated from *Xu and Stroud* (1992)

Assuming the incoming electric field is a plane wave, which is valid since more wave enter the device with a large radius of curvature, the above differential equation can be solved. A standard acousto-optical geometry is used in the solution and is shown in Figure 3-1. The acoustic wave is propagating in the x direction of the crystal causing a stress wave which leads to the modulation of the index of refraction within the acoustic region of the crystal denoted by . The system is orientated such that the acousto interaction occurs along on the z axis and the electric field entering the device is a plane wave described by

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| |  |  | | --- | --- | |  | (3.5) | | |  |  | | --- | --- | |  |  | |

and the diffracted electric field is described as

|  |  |
| --- | --- |
|  | (3.6) |

where and are the frequencies and wave vectors for the incident and diffracted beam. The modulation caused by the acoustic wave is a strain on the crystal given as

|  |  |
| --- | --- |
|  | (3.7) |

where is the angular frequency of the Radio Frequency (RF) wave, and is the acousto wave vector.

Equations 3.5 through 3.7 are used to determine the coupled wave equations by using them in the acousto wave equation, Equation 3.4. The induced polarization is formed by the incident wave interacting with the strain wave resulting in . The polarization wave will in turn stimulate the diffracted electric field yielding the first half of the coupled equations in the form

|  |  |
| --- | --- |
|  | (3.8) |
|  |  |

where is the difference between the group and phase wave vectors of the diffracted electric field, is the length of the AO interaction, and . However, once the interaction between the incident electric field forms the diffracted field, the diffracted field in turn interacts to form a polarization wave that stimulates the incident wave yielding the second coupled equation

|  |  |
| --- | --- |
|  | (3.9) |
|  |  |

with . From the previous coupled equations a very crucial concept for the operation of the AOTF is revealed known as the momentum matching criteria. The value of the exponential need to be very small or equal to zero ( *i.e.* ) for the previous interaction to have a solution and is used to find the solution. This is an important result will be used to find the tuning curve and diffraction angle within the AOTF. For Bragg diffraction the geometry is set up such that the difference of the wave vectors for the incident electric field is zero. Finally, and is the optical phase shift and the effective optical phase shift is defined as .

Solving the coupled wave equations assuming momentum matching criteria yields the following solutions

|  |  |
| --- | --- |
|  | (3.10) |
|  | (3.11) |

where which is proportional to the inverse of wavelength. It should be noted that the frequency of the diffracted wavelength is though the coupled interaction. To find the unknown coefficients, the boundary conditions of the system, are used

|  |  |
| --- | --- |
|  | (3.12) |

Solving for the coefficients yields

|  |  |
| --- | --- |
|  | (3.13) |
|  | (3.14) |

With the completed forms of the incident and diffracted fields the diffraction efficiency and the shape of the point spread function can be determined.

## 3.1.2 Diffraction Efficiency

The diffraction efficiency, of the AOTF is ratio of the energy of the incident electric field compared to the energy of the diffracted electric field at the end of the acoustic interaction region given by

|  |  |
| --- | --- |
|  | (3.15) |

This form yields the common sinc function shape for the spectral Point Spread Function (PSF) of an AOTF from a point object or source. The PSF describes the spectral bandwidth of the filtering capabilities of the device and is the limited factor to the spectral resolution of the AOTF. This limit must be sufficiently small enough (approximately less than 10 nm) to be able to accurate resolve aerosol from atmospheric measurements. However, this form can be altered to better identify how to increase the diffraction efficiency of an AOTF. The diffraction efficiency is converted into a form that uses the RF driving power assuming exact momentum matching (*i.e.* and that the interaction is occurring within a birefringent medium. The RF driving power is the amplitude at which the piezoelectric transducer pumps the RF signal into the AO medium. The average energy flow of the acoustic power is defined by

|  |  |
| --- | --- |
|  | (3.16) |

where is mass density of the medium, is the acoustic velocity in the crystal, and is the height and length of the acoustic wave interaction region. Another variable that is defined is the acousto-optic figure of merit, , which is completely determined by the medium properties defined by

|  |  |
| --- | --- |
|  | (3.17) |

and is a measure of how efficient a medium can undergo the AO effect.

Using Equations 3.16 and 3.17 along with the definition of and rearranging Equation 3.15 yields the following for the diffraction efficiency

|  |  |
| --- | --- |
|  | (3.18) |

The efficiency of the diffraction at a wavelength, , can be increased through design considerations. First, a medium should be picked that yields the largest possible AO figure of merit. Second, the active region of the AO interaction should be narrow and long increasing the ratio. And lastly, the driving power of RF wave should be large enough to equate the component inside of the sinusoid function in Equation 3.18 to . It should be noted that increasing the RF power too high can have the possibility of deceasing the AOTF diffraction efficiency.

## 3.1.3 Diffraction Angle

Although the wave equations are useful in determining the diffraction efficiency, PSF, and the form of the electric fields, it is not useful to determine the angle of the diffracted wave or the RF acousto wave to wavelength relation known as the tuning curve (covered in the section 3.1.4) instead using the momentum matching criteria realized through Equations 3.8 and 3.9.

A discussion on the diffraction angle is analyzed using the interaction between the acoustic sound wave and the phonon light by

|  |  |
| --- | --- |
|  | (3.19) |

known as the momentum matching criteria. For this analysis, only the +1 order diffraction interaction is performed although a similar analysis can be performed for the -1 case. The wave vectors are defined as

|  |  |
| --- | --- |
|  | (3.20) |
|  | (3.21) |
|  | (3.22) |

The RF frequency is given by which is related to the angular frequency by and the speed of the acousto wave within the crystal is given by . It is assumed that the extraordinary light undergoes the momentum matching through the device.



**Figure 3-2**: A standard non-collinear AOTF experiential set up. The crystal is assumed to infinitely long in the y direction. Figure recreated after *Guenther* (1990) number 14B-1.

A standard acousto optical experimental setup, which can be seen in Figure 3-2, is used to determine the diffraction angle. Using Equation 3.19, the x component of the wave vector is

|  |  |
| --- | --- |
|  | (3.23) |

and the magnitude of the diffracted wave vector is

|  |  |
| --- | --- |
|  | (3.24) |

Combining the results from Equation 3.23 and Equation 3.24 the angular deviation of the diffracted source is

|  |  |
| --- | --- |
|  | (3.25) |



**Figure 3-3**: General Layout of an AOTF. A randomly polarized incoming light source hits the front surface of the birefringent crystal. The black bar below the crystal is the piezoelectric transducer that produces the RF signal and forms the acousto wave represented by the grey arrow. The momentum matching Bragg diffraction occurs and monochromatic polarized light (-1 order) exits the AOTF at a constant angle with the 0th order and +1 order being blocked by an optical stop.

The diffracted light leaves the AOTF at a different angles depending on the RF which translates to angular movement of diffracted beam as the wavelength is scanned. In order for the device to be usable in an imaging optical system, the diffracted light must always leave the device following the same path no matter what wavelength is being filtered. Thus, a crystal wedge or compensator is fashioned to the back of the device to compensate for this effect using a correcting prism like effect causing the diffracted beam to always leave the device at the same angle. A general optical layout with the deflection in the optical path and an attached compensating wedge is shown in Figure 3-3.

## 3.1.4 Tuning Curve

The tuning curve is the AOTF relationship between the diffracted wavelength and the applied RF. The analysis is performed using the momentum matching criteria stated in Equation 3.19. Figure 3-4 shows the wave vectors in the orientation of a tellurium oxide (TeO2) crystal in a birefringent orientation where is the propagation angle of the acoustic wave with respect to the crystal orientation.



**Figure 3-4**: The wave vectors generated by the AOTF experiment set up in Figure 3-2. From the above figure and are the wave vectors of the extraordinary and ordinary axis of the AOTF crystal. Originally published as Figure 1 in *Elash et al.* (2016).

The wave vector diagram can be used to define the incident and diffracted indices of refraction in terms of the ordinary and extraordinary indices of refraction in the following

|  |  |
| --- | --- |
|  | (3.26) |
|  | (3.27) |

If the difference in the index of refraction is small, as it is for TeO2, Equation 3.26 can be approximated as (*Voloshinov et al*., 2007)

|  |  |
| --- | --- |
|  | (3.28) |

where is the difference between the extraordinary and ordinary indices of refraction (*i.e.* ). The wave vectors, seen in Figure 3-4, of the system need to follow the momentum matching criteria from Equation 3.19. Separating the wave vectors into their directional components with respect to the propagation angle, , the tangential and perpendicular directions respectively are

|  |  |
| --- | --- |
|  | (3.29) |
|  | (3.30) |

The tangential and perpendicular directions of the wave vector can be used in combination with the wave vectors definitions (Equations 3.20-3.22, and 3.29-3.30) to yield

|  |  |
| --- | --- |
|  | (3.31) |

The above can be written as

|  |  |
| --- | --- |
|  | (3.32) |

assuming difference in indices of refraction is small (Equation 3.28) and the Taylor expansion approximation of the square root is used (*Voloshinov and Mosquera*, 2006). This equation has several implications to the operation of the device which affects the design possibilities in an imaging system. First, the wavelength diffracted by the AOTF is inversely related to frequency of the RF wave. Second, the wavelength of the diffracted signal is dependent on the angle of incidence of the incoming wave therefore passing a signal though the AOTF at different incident angles results in different outgoing wavelengths. Also, through the described interaction, the diffracted light goes through a 90o rotation in polarization (*Voloshinov*, 1996). As a final note, it is important to note that the indices of refraction are sensitive to temperature changes which can alter the tuning curve calibrations, generally corresponding to a 1 nm change per 10 oC for TeO2.

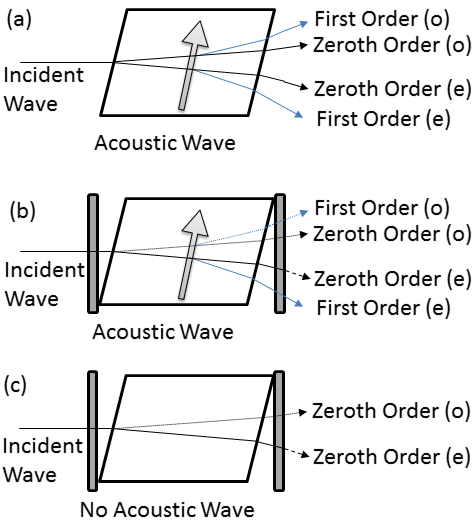
# 3.2 AOTF Calibration and Operation

An AOTF was acquired from Brimrose of America (model number TEAFI10-0.6-1.0-MSD) with a Gooch and Housego driver (model number 64020-200-2ADMDFS-A). The AOTF has a large aperture that is of imaging quality. It is optically tuned for a range of 600 nm to 1200 nm corresponding to an RF range of 156 to 75 MHz. Further the spectral resolution is 1.6 nm at 633 nm and broadens to 6.3 nm at 1153 nm with an approximately diffraction efficiently of 60% across the spectral range. The AOTF is made from a tellurium dioxide (TeO2) birefringent crystal. The extraordinary light is diffracted at 2.7o off of the optical axis of the device with a 10 mm by 10 mm optical aperture with a minimum separation angle of 6.4o between the zeroth and first order. A detailed overview of the AOTF specifications can be found in appendix A.1.3. First, a section on AOTF operation is discussed and then calibration of the device is performed. The AOTF needed to be fully calibrated to expand upon the factory specifications including:

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

## 3.2.1 Operation

Some nomenclature with regards to the AOTF’s operational states are defined. This section describes the two fundamental states used throughout the rest of this work but first is the general operation of the AOTF itself. The general operation of the AOTF is shown in Figure3-5a. In the general operation, with an RF wave applied, there is one input, the unpolarized broadband incident ray, and four output signals. The birefringence of the crystal splits the zeroth order ordinary and extraordinary polarizations into two separate outputs. The RF wave interacts with the incoming radiance to form the first order extraordinary and ordinary diffracted beams with polarizations rotated by 90o. Further, only the first order extraordinary polarization remains at a consistent angle due to the compensation mentioned in section 3.1.3.



**Figure 3-5**: (a) An AOTF undergoing Bragg diffraction with an unpolarized input incident wave with a RF wave applied represented by the arrow. After the diffraction event four output signals are formed: the zeroth order and first order ordinary (o) and extraordinary (e) signals. However the only optical path that remains at a constant angle no matter the applied RF wavelength is the first order extraordinary diffracted signal. (b) Two linear polarizers are added to the system, the first linear polarizer removes the ordinary polarization from the outputs with the dotted lines and the second linear polarizer removes undiffracted extraordinary light shown by the dashed line. This configuration is the “AOTF-on” state. (c) The system in (b) without a RF wave so no Bragg diffraction is occurring. Once again the first linear polarizer removes the ordinary polarization represented by the dotted line and the second linear polarizer removes the extraordinary light shown by the dashed line. This configuration is the “AOTF-off” state. Originally published as Figure 2 in *Elash et al.* (2016).

When the AOTF is used in any experiments or design, the removal of the unwanted polarizations are desired to achieve high quality low contamination images. As such, a linear polarizer is always placed in front of the AOTF to remove the ordinary polarization and a linear polarizer is place behind the AOTF to remove the zeroth order extraordinary polarization. When an RF wave is applied to the crystal with the polarizers, as seen in Figure 3-5b, the AOTF is considered to be in the on or “AOTF-on”state. When an RF wave is not applied to the crystal and the polarizers are present, as seen in Figure 3-5c, the AOTF is considered to be in the off or “AOTF-off” state. These two states, “AOTF-on” and “AOTF-off” are used throughout the remainder of this work to describe these two operational modes of the AOTF.

## 3.2.2 Tuning Curve Analysis

A test optical set up was devised in the lab to determine the central diffracted wavelength as a function of the selected RF, . This is known as the tuning curve.

For this analysis, a telecentric test layout was used, the details of which are described in section 3.3.1. 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 2.7o 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 3-6.



**Figure 3-6**: 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 -75oC 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 Figure 3-7a.

The tuning curve from section 3.1.4 (Equation 3.32) was not used since some of the AOTF parameters were not known and an empirical fit was used instead. The maximum values from each of the images were determined as well as the corresponding wavelengths. It was imperially noted that the curve appear to follow a power function of the form

|  |  |
| --- | --- |
|  | (3.33) |

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 was provided by a modified power function was used in the form of

|  |  |
| --- | --- |
|  | (3.34) |

The results of these fits can be seen in Figure 3-7c and Figure 3-7d. The agreement of this form is better than 0.1% throughout the whole wavelength range and the determined tuning curve is

|  |  |
| --- | --- |
|  | (3.35) |

where is in nanometers and is in megahertz with a 0.1% error in the central wavelength. Even with 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.



**Figure 3-7**: (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).

## 3.2.3 Point Spread Function

The spectral Point Spread Function (PSF) of the AOTF was also determined using the same set of data that was used to determine the tuning curve. The spectral PSF was found by determining the FWHM for each wavelength. These results are shown in Figure 3-7b. The sidelobes in Figure3-7a are a known AO effect discussed in section 3.1.2 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. 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 since aerosol is a broadband scatterer (see section 2.5.1).

## 3.2.4 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 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. 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 6o or a half angle of 3o.

# 3.3 Optical Chain Development

The ALI design goal is a simple optical system that essentially images a single wavelength at a time through the use of an AOTF. However, the AOTF operation requires important instrument design considerations to account for its optical operation (*Suhre et al*., 2004). The following sections provide a brief introduction to the two optical systems considered for ALI and an overview of the final ALI optical design. The final design images the atmosphere with a resolution on the order of 200 m for both vertical and cross-track special dimensions with a wavelength range of 600-1000 nm which corresponds to the usable range of the QSI CCD to be used in the system. Code V optical design software was used to assist in the designing and analyzing the performance of both of the optical designs and final optical system.

## 3.3.1 Telecentric System Prototype

The first optical system considered for ALI is a telecentric system which allows for the images without perspective. Before the telecentric design is discussed a basic description of a telecentric system is described.



**Figure 3-8**: A standard paraxial ray tracing diagram. The aperture is located to make the system telecentric in the image plane and is the focal length of the lens.

To describe the concept behind the telecentric system, a basic ray tracing image is shown in Figure 3-8 where three paraxial rays are drawn using a simple biconvex lens. To make this simple biconvex system telecentric in image space, an aperture is added to the system on the object side at the focal point of the lens. The theoretical idea is to have an aperture so small that only the focal ray can pass through it. All of the other rays, including the chief and parallel ray, are blocked from entering the system. Now the image is only defined by a single ray and it is in focus everywhere on the image side of the system, and therefore has an infinite depth of field. However, an aperture that is so small proposes a few problems in practice. First, a hole of such a small size would cause diffraction effects that would dominate the imaging qualities of the system. Second, such a small aperture would let so little signal through that very long exposure times would be needed or a low SNR would result. So in practice a larger aperture is used at the focal point. Now the system no longer has an infinite depth of field, but still retains a large depth of field and remains almost the same size no matter where the image plane is located. It should be noted that a telecentric system in object space can be created by putting the aperture on the image side of the lens causing the object to always be the same size in the image no matter where it is physically located.



**Figure 3-9**: Ray Tracing diagram simulation of the telecentric lens system preformed using Code V. The elements in the system are the following: (1) Optical Stop and telecentric aperture. (2) 100 mm focal length plano-convex lens. (3) Brimrose AOTF characterized in section 3.2. (4) 100 mm focal length plano-convex lens. (5) Telecentric Aperture. (6) 75.6 mm focal length plano-convex lens. (7) Imaging plane. It should be noted that the x and y scales are not the same in this image. Also, in the lab a polarizer is added in front and behind the AOTF as well as prisms after the AOTF.

A telecentric layout in both image and object space has advantages and disadvantages for the imaging quality of the AOTF system. An advantage is since the wavelength filtered by the AOTF is dependent on the incident angle (Equation 3.32) and from the ray tracing diagram (Figure 3-9), all lines of sight enter with approximately the same angular spread so the filtered image has consistent wavelength and spectral point spread function. However, two problems are added to the system. First, a blurring effect is added to the final image dependent on wavelength, which is discussed below in greater detail. As well, this method is sensitive to any surface defects of the crystal since the light enters the crystal in focused bundles.

A test optical system was designed with Front End Optics (FEO) to be telecentric in both object and image space with Back End Optics (BEO) to resize the image to fit on the CCD. A list of the specifications can be seen in Table 3-1 and a ray tracing diagram from a Code V simulation is shown in Figure 3-9. The AOTF has an optical aperture of 10 mm by 10 mm and is the field stop of the system. This is a physical limit of the device and causes the Field Of View (FOV) to be limited. In order to image the vertical limb from the ground to float altitude of a stratospheric balloon, typically 35 km, a 6o FOV is required. Also, with the current set up of 100 mm focal length lenses, the rays of light from each line of sight enter the AOTF at the maximum acceptance angle, which is 2o. The acceptance angle is the maximum angle that light can enter the AOTF aperture and still undergo efficient Bragg diffraction as measured from the normal to the face of the crystal (*Xu and Shroud,* 1992). This allows the maximum amount of light to enter the device to achieve highest possible throughput.

**Table 3-1**: Telecentric Test System Optical specifications

|  |  |
| --- | --- |
| Parameter | Value |
| Effective focal length (mm) | 75.6 |
| Front End Optics Magnification | 1.00 |
| Back End Optics Magnification | 0.756 |
| Field Of View (o) | 5.7 x 5.7 |
| F-number | 14.28 |

The image is focused on a 16-bit digital QSI 616 CCD with 1536x1024 pixels and a mechanical shutter that allows an integration time between 0.01 seconds to 240 minutes. The CCD chip itself is a Kodak KAF-1603ME with micro lenses to improve the quantum efficiency of the device and its spectral characteristics can be seen by the blue curve in Figure 3-10.



**Figure 3-10**: Quantum efficiency of the Kodak KAF-1603ME contained within the QSI CCD camera is represented by blue curve. Quantum efficiency provided by QSI Scientific.

The overall design has several aspects that make it a good system for imaging. First, all of the bundles of light entering the AOTF have the same angular spread. As seen in Equation 3.32, the diffracted wavelength depends on the incoming angle. With the telecentric layout all points of the imaging plane have the same angular dependence so the entire image is of the same center wavelength and have the similar spectral PSF.



**Figure 3-11**: The effect on the optical path of converging light bundles as they pass through a material of index of refraction . When the index of refraction strongly depends on wavelength, as in the AOTF, the optical path length can experience great changes that alters the focal point of the system.

However, despite its benefits, there are a few drawbacks to consider in the design as well. First, the optical path between the two 100 mm focal length lens is 200 mm in air for the prototype, however the AOTF is made of tellurium dioxide (TeO­­­2) or paratellurite and has a high index of refraction and dispersion given by (*Uchida*, 1971)

|  |  |
| --- | --- |
|  | (3.36) |
|  | (3.37) |

for the ordinary and extraordinary polarizations respectively. The high dispersive property, or Abbe number results in a change in the distance in the optical path, , given by

|  |  |
| --- | --- |
|  | (3.38) |

where is the index of refraction with a wavelength dependence and is the thickness of the crystal. The AOTF crystal causes the optical path in air to be lengthened by , as can be seen in Figure 3-11. In order to compensate, the length must be added to the path to account for the discrepancy, however the adjustment can only be compensated for a specific wavelength and thus a defocusing of the image plane occurs for other wavelengths. The severity of this problem can be seen in Figure 3-12 from a Code V simulation of the spot size of the optical system which was optimally focused for 800 nm. In this simulation, a grid of rays is passed through the system for each FOV and using ray tracing the final location for each FOV on the image plane are determined. The black circles represent the Airy disks, which are the minimum possible spot size possible due to diffraction for each wavelength of light. The spot sizes at 800 nm are on the order of 24 µm at the center, which is diffraction limited, and 94 µm at the edge of the FOV. However, for the same optical layout the 600 nm spot sizes are all greater than 160 µm which causes a noticeable blurring in the recorded image. For a system using a telecentic system, this defocusing of the image plane would require additional compensating optics to correct the change in the path length or the detector of the system would need to be actively moved as wavelength is scanned. However, the f-number could be increased to increase the system’s depth of field to reduce the defocusing effect caused by the AOTF, but the same effect causes a reduction in signal throughout leading to longer exposure times.



**Figure 3-12**: Code V simulation of the spot size for the telecentric system at focus at 800 nm. The spots are shown for 0.0, 1.5 and 2.6 degree fields of view at 600 nm (blue) and 800 nm (green). The full spot sizes for the 600 nm spots are 0.16, 0.22, and 0.25 mm for 0.0, 1.5, and 2.6 degrees fields respectively, with the corresponding 800 nm spot sizes being 0.024, 0.053, 0.094 mm. The black circles represent the Airy disk for each specific wavelength and FOV.

The telecentric system was breadboarded in the lab and used to image EIA 1956 standard resolution chart and the results of the test can be seen in Figure 3-13. The experimental set up is similar to the system in Figure 3-9 except for two fundamental differences. The Code V software can perform analysis for only one polarization and neglects the bend in the optical axis caused by the AOTF. However, these two issues can be dealt with sufficiently in the lab. The unwanted polarization is removed by adding a polarizer before and after the AOTF (Figure 3-5b and 3-5c). The light that is actively diffracted through the AOTF is the light that enters the AOTF crystal with extraordinary polarization. The polarizer before the device stops the ordinary polarization from entering the AOTF and the second polarizer, orientated 90o to the first, on the posterior of the AOTF is used to only let the diffracted extraordinary light through and removes the non-diffracted extraordinary polarization light. As mentioned in section 3.1.4, the polarization of the diffraction beam is rotated by 90o (*Voloshinov*, 1996). The second issue to be handled is that the AOTF bends the optical path by 2.7o. Two prisms were added after the AOTF to straighten out the optical path; the optical path past the prisms is parallel to the original optical path and is offset by approximately a millimeter and obscures a part of the field of the view. The optical layout around the AOTF is similar to the optics around the AOTF in the characterization test shown in Figure 3-4. The resolution chart was positioned so that the loss of the FOV due to the prism compensation was accounted for by a shift in the vertical location of the resolution chart.

The two images were taken, an “AOTF-off” and “AOTF-on” image, at every 25 nm at wavelengths between 600 and 1000 nm using a 30 second exposures imaged on the QSI CCD camera. The “AOTF-off” image was subtracted from the “AOTF-on” image to remove the dark current, DC offset, and stray light. Three sample images can be seen in Figure 3-13 with the optics in focused at 800 nm and the image blurring that was simulated in the spot size diagram can be easily noticed in the 650 nm wavelength image. The center lines of the resolution chart are unable to be resolved from each other compared to the 750 nm image. A unique line of sight can be resolved every 2 pixels in the center of the 750 nm image which corresponds to 150 m resolution at the tangent point from the balloon platform, and a 4-5 pixel resolution near the edge corresponding to about a 200 m resolution. Also due to the efficiencies of the CCD and the charts ability to reflect the longer wavelengths of light the SNR at the 850 nm image in the bottom right panel is rather low, and can be visibly seen by looking at the grainy quality of the image.



**Figure 3-13**: The top left is the original test image used for the experiment. The top right, bottom left, and bottom right are the images recorded through the telecentric system at 650, 750, and 850 nm. The system is focused at 800 nm.

## 3.3.2 Telescopic System Prototype

The second optical system in consideration is a telescopic optical system configuration consisting of a standard telescope for the FEO with a focusing lens. The front lens, known as the objective lens, is used to focus an object at infinity to the focal point of the lens, then a second lens, the eyepiece is used to increase the optical power of the system, that is to increase the angular size of the image with respect to the angular size of the object. The eyepiece lens is located at a combined distance of the focal lengths of both the objective and eyepiece and causes the image to be focused at infinity. However for our system the telescope is used to focus the light in order to enter the AOTF at an angle less than its acceptance angle as well as to reject light rays outside of the desired FOV. The light from each line of sight in the telescopic system enters the AOTF collimated and is focused though the BEO onto the QSI 616 CCD discussed in section 3.3.1. A detailed simulation Code V layout and ray tracing of the optical design can be seen in Figure 3-14.



**Figure 3-14**: Ray Tracing diagram of the telescopic lens system simulated by Code V. The elements in the system are the following: (1) 100 mm focal length plano-convex lens. (2) Location where field stop is located to limit stray light (3) 100 mm focal length plano-convex lens. (4) Brimrose AOTF characterized in section 3.2. (5) 75.6 mm focal length plano-convex lens. (6) Imaging plane. It should be noted that the x and y scales are not the same as Figure 3-9. Also, in the lab a polarizer is added in front and behind the AOTF as well as prisms behind the AOTF.

The telescopic prototype was designed with as many similar components and specifications as possible to the telecentric prototype in order to allow accurate comparisons of the systems without major optical effects and aberrations caused by using different materials, sizes, and focal length lenses. The optical specifications of this system are given in Table 3-2. However, there are a few fundamental differences. First, the aperture stop is located at the front lens which limits the rays of light that can enter the system, unlike the telecentric design that has a front aperture stop at the focal length of the first lens.

**Table 3-2**: Telescoptic Prototype System Optical Parameters.

|  |  |
| --- | --- |
| Parameter | Value |
| Effective focal length (mm) | 75.6 |
| Front End Optics Magnification | 1.00 |
| Back End Optics Magnification | 0.756 |
| Field Of View (o) | 6.0 x 6.0 |
| F-number | 20 |

The second fundamental change to the optical system is that the AOTF now has collimated light passing though the device, unlike the telecentric system, and this has a few changes to improve and degrade the imaging quality of the system. First, the primary light passing through the AOTF from a single line of sight is entering the AOTF at the same angle, so the image has a smaller spectral PSF than the telecentric counterpart; however, each line of sight is diffracted with a different fundamental wavelength due to the angular dependence in the AOTF Bragg diffraction wavelength determination (Equation 3.32). The final image has a smaller spectral bandpass but there is a wavelength gradient radiating out from the center of the image. Second, since the light now passes through the AOTF collimated, the focal point of the image no longer changes with wavelength. Instead, a lateral displacement of each line of sight occurs based on the angle of incidence and the diffracted wavelength which causes a slight magnification of the image. The lateral displacement that occurs is given by the following relation

|  |  |
| --- | --- |
|  | (3.39) |

where is the displacement from the original path; causing a slight magnification change based on the wavelength of the light being diffracted and is the incident angle on the crystal. However, this wavelength dependent change is less than a micrometer for the test configuration and is considered negligible. The effect can be seen in Figure 3-15. The last change to the system is the focusing power it possesses, as can be seen in the spot diagrams in Figure 3-16. The change in spot size due to wavelength is primarily due to the chromatic aberrations of the optical lenses. One option is to replace the lenses with mirrors in the flight version which eliminates the chromatic aberration issue, the second is to use achromatic doublets to remove the chromatic aberrations. Second, the system is diffraction limited for 600 nm for all lines of sight and for 800 nm at 3.0 degrees. Also the difference in location of the spot sizes is caused by the magnification effect discussed above.



**Figure 3-15**: Vertical displacement of a collimated bundle of light cause by a material of index of refraction .



**Figure 3-16**: Code V simulation of the spot size for the telescopic system. The spots are shown for 0.0, 1.5 and 3.0o fields of view at 600 nm (blue) and 800 nm (green). The full spot sizes for the 600 nm spots are 0.004, 0.045, and 0.122 mm for 0.0, 1.5, and 3.0o fields respectively, with the corresponding 800 nm spot sizes being 0.096, 0.081, 0.047 mm. The black circles represent the Airy disk for 600 nm wavelength and each FOV.

An experimental resolution test was set up with the telescopic system with two polarizers and prisms added to the optical chain in the similar fashion to the section 3.3.1 experimental set up. The QSI CCD was also used with the same 30 second integration time. The results of this test can be seen in Figure 3-17. Once again the image at 750 nm is the sharpest of the three but the center lines of the EIA 1956 test chart are distinguishable at all of the wavelengths. The blurring of the 650 nm image is caused by the chromatic aberrations of the lens and the prisms. Furthermore the prisms are removed in the final design reducing the aberrations. Also, the magnification issue discussed above is relatively insignificant in the test images and the small changes can be accounted for in the calibration of the final instrument. Lastly, the resolution target’s poor ability to reflect NIR radiation of the light source causes the 850 nm image to also have a low SNR. This issue is not be a concern for the final system.

C:\Users\bje035\Documents\telescopic.tif

**Figure 3-17**: The top left is the original test image used for the experiment. The top right, bottom left, and bottom right are the images recorded through the telescopic system at 650, 750, and 850 nm. The system is focused at 800 nm.

## 3.3.3 ALI Optical Design

In light of the requirements for imaging aerosol, we have chosen a telescopic design for the ALI prototype. Since the wavelength gradient across the image is small compared to the slowly varying aerosol scattering cross section, the fixed image plane is preferable for the improvement it provides in spatial imaging, particularly as we desired to use as simple as possible an optical design.

We used a very simple three lens optical layout with commercial off-the-shelf components. Two lenses before the AOTF form a simple telescope for the Front End Optics (FEO), and a single focusing lens behind the AOTF comprises the Back End Optics (BEO). The AOTF is oriented such that the detected image is formed from the diffracted beam of the vertically polarized, i.e. extraordinary, light (defined at the entrance aperture). A linear polarizer with an extinction ratio greater than 105 is placed at the back of the FEO to remove the incoming horizontal, or ordinary, polarized beam. The diffracted extraordinary beam undergoes a 90o rotation in polarization so a second linear polarizer, oriented at 90o to the first, is used after the AOTF but before the BEO to remove the undiffracted beam. This is shown schematically in Figure 3-5b. Note that even with the high extinction ratio of the polarizers, a not insignificant fraction of light that is intended to be blocked passes through the system. The diffracted extraordinary signal comprises at most a ~10 nm bandpass fraction of one polarization such that the unabsorbed broadband signal from the polarizers can be on the same order of intensity as the diffracted signal.



**Figure 3-18**: Final optical design for ALI with a Code V ray tracing diagram. The elements in the system are: (1) 150 mm focal length plano-convex lens. (2) Field stop. (3) 100 mm focal length plano-convex lens. (4) Vertical (extraordinary) linear polarizer. (5) Brimrose AOTF. (6) Horizontal (ordinary) linear polarizer. (7) 50.4 mm focal length bi-convex lens. (8) Imaging plane. Originally published as Figure 4 in *Elash et al.* (2016).

The extraordinary diffracted light is 2.7o from the optical axis and to compensate, the entire optical chain after the AOTF is mechanically aligned with this direction. The BEO forms the image of the signal on a QSI 616s 16 bit CCD with 1536 by 1024 pixels. A ray tracing diagram for ALI's optical system was created using the Code V optical design software and can be seen in Figure **3-18**. No corrections were attempted to reduce chromatic or spherical aberrations within the system and the system exhibits coma due to a large field of view and the curvature of the lenses near the edge of the field of view. Analysis with Code V shows that the distortion due to these effects across the center two degrees of the field of view is a change of less than 1% across the entire wavelength range. The final one degree shows a distortion of less than 4%.

An analysis was also performed to determine the minimum resolution required to achieve a Modular Transfer Function (MTF) of 0.3 across the entire field of view for all wavelengths (*Smith*, 2000). The MTF is an optical measure of the system’s ability to resolve line pairs per millimeter where a line pair is a white line followed by a black line. Generally, when increasing line pairs per millimeter leads to a decrease in the resolvability of an optical system. The MTF can be found computationally through

|  |  |
| --- | --- |
|  | (3.40) |

where the MTF is dependent on the frequency, , of the line pairs, is the maximum intensity of the measured pair, and is the minimum. The MTF can vary differently with respect to tangential and radial directions of the optic system. To obtain a minimum MTF of 0.3 across the entire field, except for the 3o tangential or perpendicular FOV, a seven pixel running average is required, corresponding to a MTF frequency of 15.5 line pairs per millimeter. The 3o tangential field being below the detection threshold of 0.3 is not a large concern since the SNR is low at the edges of the FOV and primality results in a loss of cross-track resolution at the ground and float altitude tangent points which are not critical for analysis. Furthermore, when the FOV is 2.7o from the normal the tangential component is above the 0.3 MTF threshold. The MTF analysis of ALI can be seen in Figure 3-19. Overall, this corresponds to an average vertical and horizontal resolution of 210 m across the entire ALI field of view at the tangent point.

A tolerance study was also performed with Code V to assess the capability of the system within the tolerances of the mounting equipment. Through a Monte Carlo method, Code V perturbs the placement and shape of the optical components within the system and computes the change in the MTF on the image plane. This analysis determines what optical misalignments or defects will degrade the performance of the system. Performing the analysis on ALI, it was determined that ALI was relatively insensitive to the tolerances of commercial off-the-shelf component used.



**Figure 3-19**: MTF analysis performed by Code V for the final ALI design used in campaign. The 7 pixel running average corresponds to a spatial frequency of 15.5 cycles/mm.

**Table 3-3**: Final ALI optical specifications

|  |  |
| --- | --- |
| Parameter | Value |
| Effective focal length (mm) | 74.3 |
| Front end magnification | 0.67 |
| Back end magnification | 1.27 |
| Entrance Pupil (mm) | 9.91 |
| Field of view (o) | 6.0 x 5.0 |
| F-number | 7.5 |
| Image size (mm) | 9 x 7.5 |
| Image size (pixels) | 1000 x 800 |
| Resolved image size (averaged pixels) | 143 x 114 |
| Spectral range (nm) | 650-950 |

An experiment to determine the exposure times and entrance pupil of ALI is discussed in the calibrations section specifically in section 3.6.1 but the results of the experiment were that the ALI entrance pupil was selected at 9.91 mm to yield estimate flight exposure on the order of a second. Furthermore, a demagnification in the FEO and a magnification in the BEO was added to further increase the light throughput to help reduce the exposure times. A summary of the optical specification for the ALI prototype is given in Table 3-3. It is important to note that a camera could not be acquired to be able to capture the entire desired range 600-1200 nm and instead a reduced range is measured from 650-950 nm. Although quality aerosol extinction measurements can still be made with this range the instrument does lose some sensitivity to particle size distriibutions.

It should be noted that our choice of a telescopic optical layout for ALI is actually the opposite choice of that made for the ALTIUS design, which uses a telecentric optical layout. For that instrument, the need for spectral resolution for trace gas retrieval makes the decision to use telecentric optics quite clear (*Dekemper et al.*, 2012). Given that basic design difference, the overall optical specifications are quite similar between the ALI and ALITUS prototype instruments (again see Table 3-3 for ALI specifications), although two key differences are noted. First, by using a telescopic layout the maximum field of view for ALI is determined by choosing lenses to ensure light enters ALI within the acceptance angle of the AOTF. This allows for a larger possible field of view than with a telecentric system where the field view is defined by the aperture of the AOTF. Second, the f-number for ALTIUS is 14.32 compared to 7.5 for ALI, which allows ALI to increase light throughput at the cost of slightly higher aberrations in the final image. *Dekemper et al.* (2012) reports that the visible channel of ALTIUS was breadboarded and tested by taking ground based measurements of a smoke stack plume. They used the measurements to retrieve NO2 slant column density using 10 second exposure times; although, they note that an increase in measurement frequency would improve the instrument capabilities. This also factored into our decision to use telescopic optics to increase throughput for ALI. A final selection for the optical design of ALI was presented in this section as well the justifications used to determine the result. For the final design of ALI, the telescopic system deemed to be the better option for our scientific purpose to determine aerosol extinction and engineering study to verify the capabilities of using an AOTF in space based remote sensing techniques.

## 3.3.4 Correction to the Optical Design

It should be noted a correction to the optical design is required that was discovered after the campaign of the instrument during the analysis. For the 3o FOV the light enters the AOTF at an angle of 2.2o from the normal and the acceptance angle of the AOTF is 2.0o. This results is a great loss of diffraction efficiency for the last approximately half degree of the field of view. This error was created when decreasing the f-number of the system to 7.5 to reduce the exposure times, remembering that lower f-numbers have higher light throughput, by adding a FEO magnification. However, this increase in throughput is overcompensated by the loss in diffraction efficiency of the AOTF overall resulting in a lower SNR. To rectify this problem a slight change to the optical system is suggested in this section while still using commercial off-the-shelf components.

The main issue results about the front end magnification and the suggestion resolves around keeping a similar optical layout with a smaller demagnification in the FEO, and a compensating demagnification with the BEO to maintain the same final image size. This is performed by replacing the first lens or objective lens of the telescope (element 1 in Figure 3-18) to a 125 mm focal length plano-convex lens and compensating the optics such that the distance between the first two lenses is the sum of the two focal lengths of the telescope. The back end lens is also replaced with a 62.9 mm bi-convex lens. This results in the 3o FOV entering the AOTF at 1.6o well within the acceptance angle of the AOTF. A table of the revised specifications can be found in Table 3-4.

This change results in several secondary changes to the system. First, the f-number is increased up to 8.0 which reduces the throughput of the system over but the last half of a degree of the field of view becomes brighter helping to reduce the vignetting and SNR drop off near the edge of the measured images. Second, the size of the image on the CCD has reduced in size which should decrease the resolution of the instrument but the decrease is partially offset by the larger f-number reducing the system aberration resulting in a final average vertical horizontal resolution of 260 m.

**Table 3-4**: Revised ALI optical specifications

|  |  |
| --- | --- |
| Parameter | Value |
| Effective focal length (mm) | 78.9 |
| Front end magnification | 0.80 |
| Back end magnification | 0.98 |
| Entrance Pupil (mm) | 9.91 |
| Field of view (o) | 6.0 x 5.0 |
| F-number | 8.0 |
| Image size (mm) | 8.5 x 7.1 |
| Image size (pixels) | 945 x 789 |
| Resolved image size (averaged pixels) | 135 x 114 |
| Spectral range (nm) | 650-950 |

# 3.4 Opto-Mechanical Design and Thermal Balancing

Upon the finalization of the optical design of the system, an opto-mechanical system was required for use of a stratospheric balloon. This section gives an overview of the hardware used to transform ALI from a laboratory breadboard to a flight model. The opto-mechanical design discusses the optics component framing within the system, stray light reduction, as well as the addition of a light tight case. Following is a brief overview of the thermal concerns of the system and how the system was designed to minimize the thermal risks.

## 3.4.1 Opto-Mechanical Design

After the optical system had been finalized, an opto-mechanic design to secure the optical components was required. The opto-mechanical system needed to be able to withstand the stresses applied to the system during the launch of the stratospheric balloon and to withstand the large thermal changes that could be experienced during the flight to keep the optics in the system aligned and in focus. Furthermore, the system must also meet safety factors for torque and shock forces on the instrument so that it does not become detached from the gondola during the flight. This is to verify the safety of CNES workers who launch the balloon as well as citizens below the gondola during flight.

Consideration for thermal expansion and contraction of the opto-mechanical components also had to be considered when picking materials to house the optical lenses housing system in order to reduce the chance of any torques arising in the optical chain from thermal expansions. To reduce this effect, a consistent material was picked for the complete optical housing so all materials would have the same thermal response to the environment with which it is exposed. The chosen material was aluminum since it is commonly used in stratospheric balloon instruments and platforms because of its light weight and relatively inexpensive cost.

With a chosen material the next design parameter was what method to use to house the optics. Commonly, space based instrumentation uses a solid piece of material and is machined into the shape required to be able to house all the optical components. However, this method is relatively expensive and is generally used for finalized space instrumentation and not for design concept prototypes. These types of cases also have a long lead-times for the production and manufacturing components which would have been pressing our timeline for the launch date. The other option was to design an optical rail system primarily from off-the-shelf components from optical manufacturers, which would allow the flexibility to be able to make slight modifications to the design without having to commission a new one-piece case allowing for inexpensive alterations to the ALI optical chain without complete reconstruction. The drawback with only using off-the-shelf components is it may be harder to maintain the alignment and resolution of the system. Considering the prototype nature of the project, the choice was made to go with off-the-shelf opto-mechanical and structural pieces for ALI with the possible limitation in alignment and resolution being classified as an acceptable trade-off.



**Figure 3-20**: The final optical layout of ALI's optical chain from the top and profile perspectives with the components being the following: (1) 150 mm plano-convex lens with 25.4 mm diameter. (2) Field Stop. (3) 100 mm plano-convex lens with 50.8 mm diameter. (4) Optical rail system. (5) Vertical (extraordinary) linear polarizer. (6) Brimrose AOTF. (7) Rotation Stage. (8) Horizontal (ordinary) linear polarizer. (9) 50 mm bi-convex lens with 25.4 mm diameter. (10) QSI 616s CCD camera. (11) Optical rail.

Using components from ThorLabs, Edmund Optics, Newport, and McMaster-Carr, an opto-mechanical case was designed for ALI and can be seen in Figure 3-20. A single sturdy wide optical rail, element 11, was used as the system base since it has the whole optical chain plus a baffle (see section 3.4.2) mounted to it and would have a low suitability to torsion. This rail would serve as a base for all the optical mounting. The opto-mechanical chain was connected to the rail using rigid optical aluminum rods. For the optical chain, an optical cage system was used since the four rods surrounding the optic mounts provided a rigid framework that would still allow for fine tuning of the optical elements. The optical cage is element 4 in Figure 3-20. Once the aligning of the optical system was completed, the components were glued into place to prevent slippage during transportation and flight.

During the testing of the breadboarded optical system in the lab, two prisms were used to account for the deviation in the optical chain caused the AOTF. These prisms were removed in the final design by bending the BEO of the optical chain by 2.7o through a rotation stage (element 7). The removal of the prisms further reduced distortions within the system.

It should be mentioned that optical lenses for ALI were repurchased for the final system with the addition of antireflection coatings. An antireflection coating would increase the systems efficiency. From ThorLabs, a B-type antireflection coating was ordered for the lenses which reduces reflection from each lens surface down to an average of less than 0.50% from 650 to 1050 nm instead of an approximately 8% loss per surface from an uncoated lenses. The lenses also had a 1% tolerance in the focal length and made from grade A NBK7 glass.

A selection of linear polarizers were considered for elements 5 and 8 in the opto-mechanical system. However, the wavelength range of ALI made standard polarizers difficult to find which limited the possible choices. A nanoparticle linear film polarizer from ThorLabs was eventually decided upon (model number LPVIS100) for ALI since it gave an extinction ratio better than 105 for 650 to 1200 nm completely covering ALI operating range. The extinction ratio is defined by the ratio between the maximum transmission when the polarizers axis is aligned with the signal to the minimum transmission after the polarizer has been rotated by 90o.



**Figure 3-21**: The custom mounting hardware design to mount the AOTF and QSI CCD camera into ALI's opto-mechanical design. Left: Custom AOTF mounting hardware. Right: The five piece QSI CCD camera mounting hardware.

For the opto-mechanical design special consideration had to be given to mounting the AOTF and CCD camera. Both of these elements are non-standard sizes in optics and no preexisting components could be purchased to mount these pieces. Therefore custom mounting pieces had to be used to rigidly mount these components. Both components were designed though the used of the SolidWorks design software.

The AOTF had one usable mounting hold on the bottom of the device to affix the device to the optical chain. However, directly mounting the device onto the rotation stage would result in the AOTF being offset downward from the optical path. Furthermore, with only one mounting point there was concern for rotation of the device rotating during the flight which would not be able to be mitigated. A single piece was designed that lightly clamped the AOTF onto the top of the mounting hardware to lock the AOTF's rotation axis. To mount the custom AOTF mount to the optical system four tapped screw holes were utilized on the top of the rotation stage. On the base of the AOTF mount two slot screw holes were used to be able to correctly align the AOTF within the optical chain when affixing it to the rotation stage which can be seen in the left side of Figure **3-21**.

The mount for the CCD camera had a different set of requirements; mounting holes were available for use on the bottom of the camera but the camera mount needed to be able to securely hold the relatively heavy camera into place with very little available vertical space (~6 cm) between the base of the rail mount and the camera. A five piece mount was designed that would fit in the tight space and be sturdy to support the mass of the camera seen in the right side of Figure **3-21**. The base plate perfectly fits onto the optical rail mount and the slotted holes allow for horizontal alignment of the camera with the optical axis. The vertical alignment to the optical axis is correctly set with the height of the camera mount. Also, the CCD sensor on the QSI camera is offset to one side and the mounting hardware accounts for this displacement.



**Figure 3-22**: ALI opto-mechanical system with three degree horizontal tilt and designed baffle discussed in section 3.4.2. Originally published as Figure 5 in *Elash et al.* (2016).

The ALI system is tilted three degrees from the horizontal so that the FOV of the instrument from the balloon flight geometry would measure from the ground to the balloon float altitude. A SolidWorks rendition of ALI with the three degree tilt from the horizontal can be seen in Figure **3-22**.

Finally, mounting hardware was tested through simulations done by the CSA to verify that the safety factor of the system was met, which it passed. The test was a stress analysis of the mounting points of the ALI system to the gondola and itself.

## 3.4.2 Baffle Design

A major concern with any optical instrument is the presence of unwanted or stray light. Two types of stray light are commonly defined: internal and out-of-field stray light. Internal stray light is unwanted light that passes through the system through scattering, reflections, or imperfections in optical elements. Out-of-field stray light is light that enters the optical path but originates from outside of the field of view. A long standing concern in the design of limb scatter instruments is the effective rejection of out-of-field stray light. This is due to the bright surface very near to the targeted limb in combination with the exponentially dropping limb signal with tangent altitude. For ALI test observations from the stratospheric balloon, a front end baffle was incorporated.

When designing a baffle several design aspects need to be considered. Consideration must be given to the length and width of the baffle as a larger, well-designed baffle is able to more efficiently remove out-of-field light but increases the size, mass, and cost of the instrument. Furthermore, the number of vanes in the baffle design must be considered. More vanes help to remove additional out-of-field light but each vane adds an edge that light can scatter off which may introduce more stray light into the system. A balance must be met with the size and number of vanes in the ALI baffle to best remove out-of-field stray light.

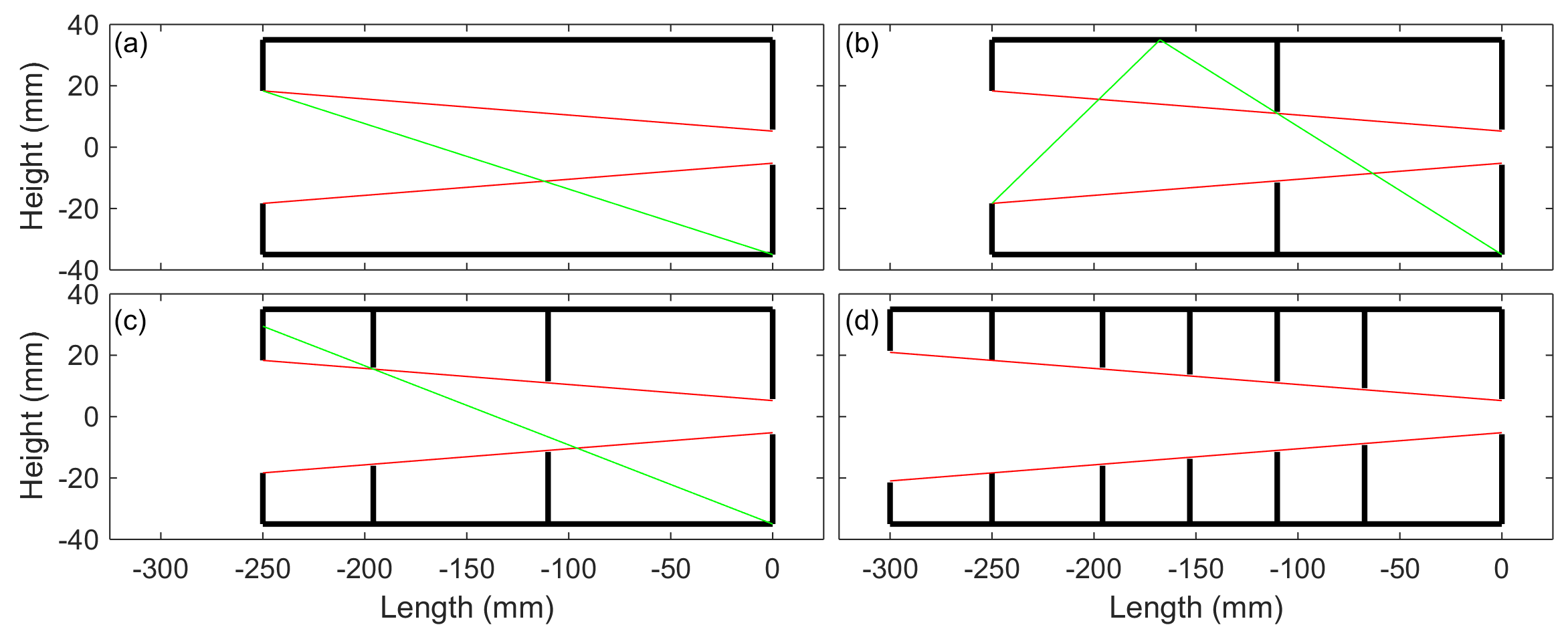
The first point of the discussion is the height and width of the baffle. In a baffle system, the larger the baffle is by cross-sectional area the better the baffle can be designed to reduce stray light. However, there is a limited amount of space to build the ALI instrument and the baffle must share space with optics, electronics and power systems; and as such, a size that fit these constraints had to be selected. An internal height and width of 70.00 mm was chosen since this was the size of the optical rails used to house the optical chain and the instrument could not be any taller than the height of the optical rail to meet size constraints.

The length is also limited by the space available, as well as the field of view and entrance aperture size. The baffle must be short enough so that the size of the field of view does not become larger than the cross-section of the baffle. To maximize the effectiveness of the baffle the longest possible length that could be accommodated was selected and was 300 mm in length.

Also, one always needs to make sure the optical stop located within the baffle is placed at the same location as the optical design. If the location of the optical stop is changed from the baffle design, it affects the performance of the instrument itself. If the optical stop is moved further from the optical design specifications, the field of view remains the same but limits the amount of light that enters the system. Thus changing the overall f-number of the system either increases the exposure times or decreases the SNR. The other case is if the optical stop is moved closer to the optical system. The opposite problem occurs which is more light enters the system than the system was designed for causing an excess of stray light and rendering the baffle ineffective.

The baffle system is designed such that it minimizes the percentage of out-of-field stray light that enters the system without encountering at least three baffle surfaces. This method, the optimal baffle geometry, is standardly used in optics to minimize stray light (*Fischer*, 2008). In the system, the baffles are spaced in such a way that little stray light can enter the system without coming into contact with at least three surfaces reducing the overall intensity of the light stray.

The optimal baffle geometry design method is described. In Figure 3-23a the base baffle case is formed with the critical baffle vane at the entrance to the optical system (-250 mm) and a second vane is located closest to the optical chain. It should be noted that a reduction in the length of the baffle to 250 mm occurred so that an exterior baffle could be added to reduce surface reflections. The marginal rays of the optical system is represented by the red line.



**Figure 3-23**: (a) Start of the optical baffle geometry method. The red lines are the marginal rays and the green line is the first ray that can enter the system without encountering at least three surfaces. (b) The first internal vane has been added and the location of the next vane is being determined. (c) The second internal baffle has been added and since the green line intersects with the critical baffle no more baffle are required. (d) Additional interior vanes and an external vane have been added to ensure a height to pitch ratio of 0.5 to improve the baffle’s capabilities to reduce stray light.

Next, an indicator line is drawn from the bottom right corner of the baffle to the opposite tip of the critical baffle, represented by the green line. This line represents the first ray that can enter the system without coming into contact with at least three surfaces. The next vane is added where the indicator line and marginal ray intersect as can be seen in Figure 3-23b.

The next indicator line goes from the bottom corner to just passing the first vane and encounters the outer side of the baffle wall. The line goes through a reflection and passes just by the critical baffle once again. The intersection of the second segment of the indicator line and marginal ray is where the second vane is added as in Figure 3-23c.

The process is then repeated to determine the location of any additional vanes. For the ALI baffle, the indicator line no longer is able to reflect upon the top baffle surface and therefore the minimum level of baffles have been achieved. However, two extra internal baffles and one external baffle were added to the design (Figure 3-23d). The exterior baffle was added to help further reduce stray light from surface reflection by shielding the critical baffle from the direct ground reflections. The additional interior baffles were added to achieve a height to pitch ratio greater than 0.5. If the height to pitch ratio is less than 0.5, additional stray light enters the optical system due to the high amount of empty space within the baffle (*Fischner*, 2008).



**Figure 3-24**: A cross-section view of the ALI baffle system. All dimensions on the drawing are in millimeters and the sloped black lines show the 6 degree field of view.

With the completed design, a drawing needed to be created to machine the baffle accounting for machining tolerances. With the exception of the critical baffle all of the edges of the vanes were reduced in size by 0.5 mm so that they could be produced within possible machining tolerances and not limit the FOV by being too tall. A SolidWorks version of the baffle can be seen in Figure 3-24 which accounts for the thickness of the materials and machining tolerances.



**Figure 3-25**: ALI baffle vain profile. Dimensions are in millimeters.

Ideally, the edges of the vanes would be machined to a fine blade. However, this is not practical for two reasons. First, the baffle’s edges would be prone to damage causing dents or groves in the vane cross-section possibly producing unwanted scattering effects. Second, it is only possible to machine the tips so fine with tolerances without reducing the height of the vane. Figure3-25 shows the profile for the baffle vanes as they were machined. A final assembly of the optical system can be seen in Figure 3-26.



**Figure 3-26**: Final ALI optical and opto-mechanical assembly.

## 3.4.3 Light Tight Case

To complete the opto-mechanical design, a light tight case was required. The case was made out of aluminum and every connection point in the case was overlapped, through interlocking pieces, to verify the rejection of the light. The light tight case was clamped onto the base plate of ALI and a final rendition of ALI can be seen in Figure 3-27.



**Figure 3-27**: ALI optical system with light tight case attached. Three degree horizontal tilt not present in this image.

## 3.4.4 Thermal Considerations

An instrument, like ALI, has to survive the possibility of extreme temperatures during a flight on a stratospheric balloon. The extreme temperatures arise though various processes, first the instrument must survive the assent through the tropopause where temperatures can reach -70oC and must survive the float temperatures which can be as cold as -50oC. Conversely, being exposed to direct sunlight causes heating that would result in instrument failure due to overheating. Furthermore, ALI using simple opto-mechanical design means there is no active thermal control and, with the reduced atmospheric density at approximately a float altitude of approximately 35 km convective cooling could not be relied on for thermal control. Following is a discussion of various thermal concerns within ALI.

The electronics are stored within two aluminum cases, a computer case and power supply case. All components within the two cases are all rated for an extended thermal range (-40 to 85oC) except the RF driver which has an operational thermal range of 0 to 50oC. The extended range of the all other electronic components reduces the concern since this case is not be exposed directly to the elements as they are sheltered via insulation and, from consultation with the CSA and CNES teams, the internal temperature of the electronics area from previous missions have reached a coldest temperature of approximately -20oC during normal flight operations.

However, the RF driver does not fall into the specified temperature range, which is a problem, and the driver also produces a large amount of heat that is convectively cooled on the surface which is not possible at float due to the reduced atmospheric pressure. Since the RF driver is a fundamental piece of hardware, failure in the component would result in a primary system failure.

To mitigate the risk, several considerations are made with regards to the RF driver. First, a RF driver with a cooling plate is purchased to better allow for conductive thermal control and without any method of cooling the driver on the gondola the driver would overheat and fail. So the driver is mounted to the aluminum case such that the cooling plate would be in direct contact with the surface of the case, and the case would be mounted on the gondola such that the surface of the case would be against the aluminum mounting surface on the gondola. This allows a large amount of heat to be dumped to the gondola to keep the RF driver within the operating range. Second, the driver freezing was not as large of a concern since the driver produced enough heat to sustain its temperature. However, the driver would be both on and off during the mission for different imaging modes which may result in freezing or overheating. A temperature sensor is used to monitor the driver and the control software on board ALI has a safety measure built in that would automatically turn the driver off if it reached 50oC or turn on if the temperature dipped below 0oC.

Another region of concern was the housing of the optical system which would be directly exposed to the elements. The optics would expand and contract based on the temperature and CCD camera had an operating temperature of -40 to 20oC. Furthermore, the CCD primarily used convection to cool the camera; by recommendation from QSI, fans were disabled as they would rip apart due to the low atmospheric pressure since the rotation speed is based on air resistance. To mitigate the thermal risk, a twofold approach was taken. First, the optical housing was surrounded in foam to thermally insulate it from the cold experienced during darkness and assent though the tropopause. Second, the foam insulation was covered in a reflective material to reduce direct warming from the radiation from the sun.

# 3.5 Control Software

During the stratospheric balloon flight, software is needed in order to control the instrument from the ground and have it operate in the air. To accomplish the communication and control systems needed, two separate software packages were developed. First, a ground control platform that communicated to ALI and to receive diagnostic information, completed images, and to send commands to be processed. The second software package was the onboard system to control the instruments systems.

The ground control software contains the single 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 85oC. 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 3-28 by blue, green, orange, purple, and yellow respectively.



**Figure 3-28**: 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 terminate 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.

The diagnostic module manages the Global Positioning System (GPS), pulse per second, and the 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. Lastly, the temperature sensor module reads all of the temperature sensors from a one line temperature sensing device, where all temperature sensors are on a single line and are connected with a simple RS-232 connection. The locations of the temperature sensors can be seen in Table 3-5 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 3-5**: 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 files 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 contain the needed housekeeping measurements and five vertical image profiles 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.

A diagnostic image is sent down for every image during the mission. 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. It can land in water and the data be lost or crash land destroying the stored data. In case of the occurrence 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.

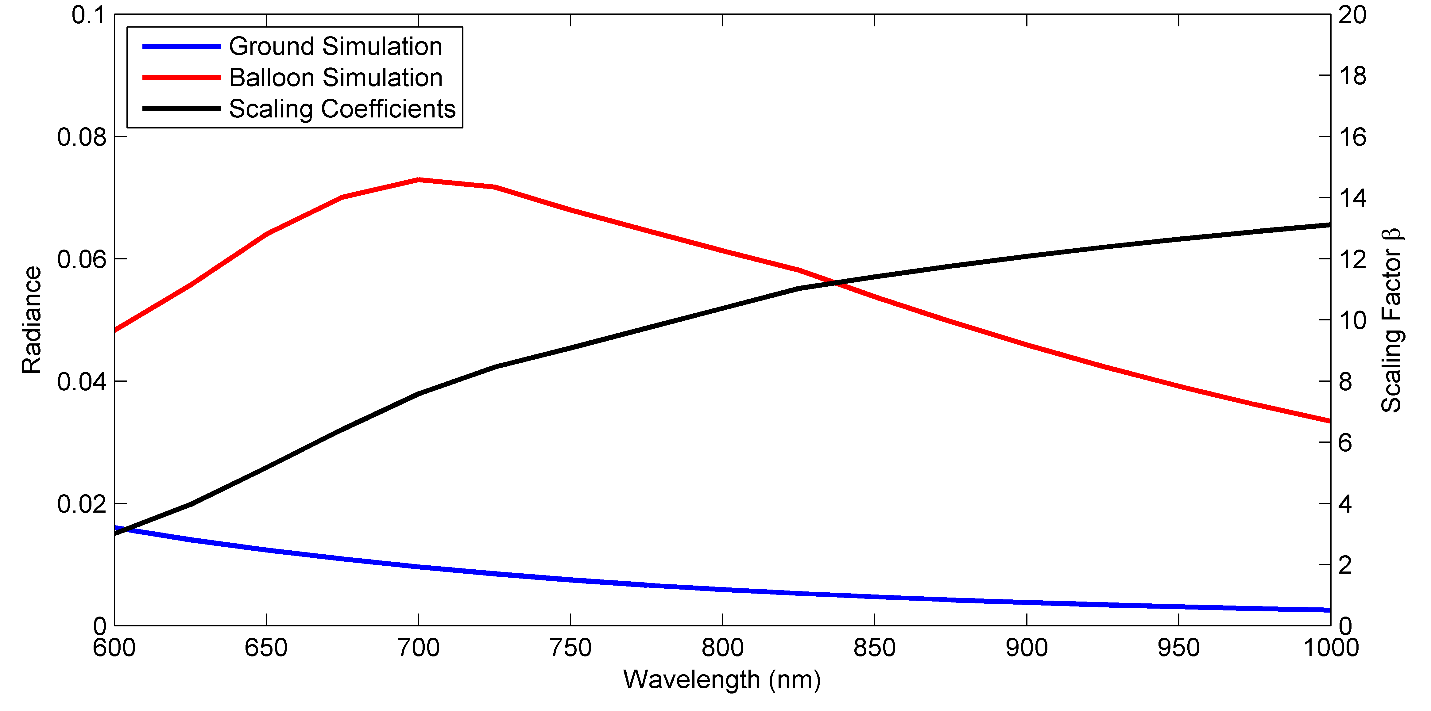
# 3.6 ALI Calibrations and System Test

A series of pre-flight laboratory calibrations were performed on ALI. The instrument was characterized as a complete system to provide calibrated radiance and estimate flight exposure times. Furthermore, complete system tests were performed to assess the full system in operation and address any issues or concerns. The following calibration measurements were performed on ALI:

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

## 3.6.1 Exposure Time Determination

A test 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 (52.13oN 106.63oW) pointing approximately 90o 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.



**Figure 3-29**: 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.

In order 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 Figure 3-29. Radiance profiles based on the ratio of the ground based and balloon based geometries were used as a scaling factor, . The scaling factor can be used in combination with the ground based determined integration times, in the following

|  |  |
| --- | --- |
|  | (3.41) |

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 Figure **3-29** and the estimated balloon geometry exposure times are located in Table 3-6.

**Table 3-6:** 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 |

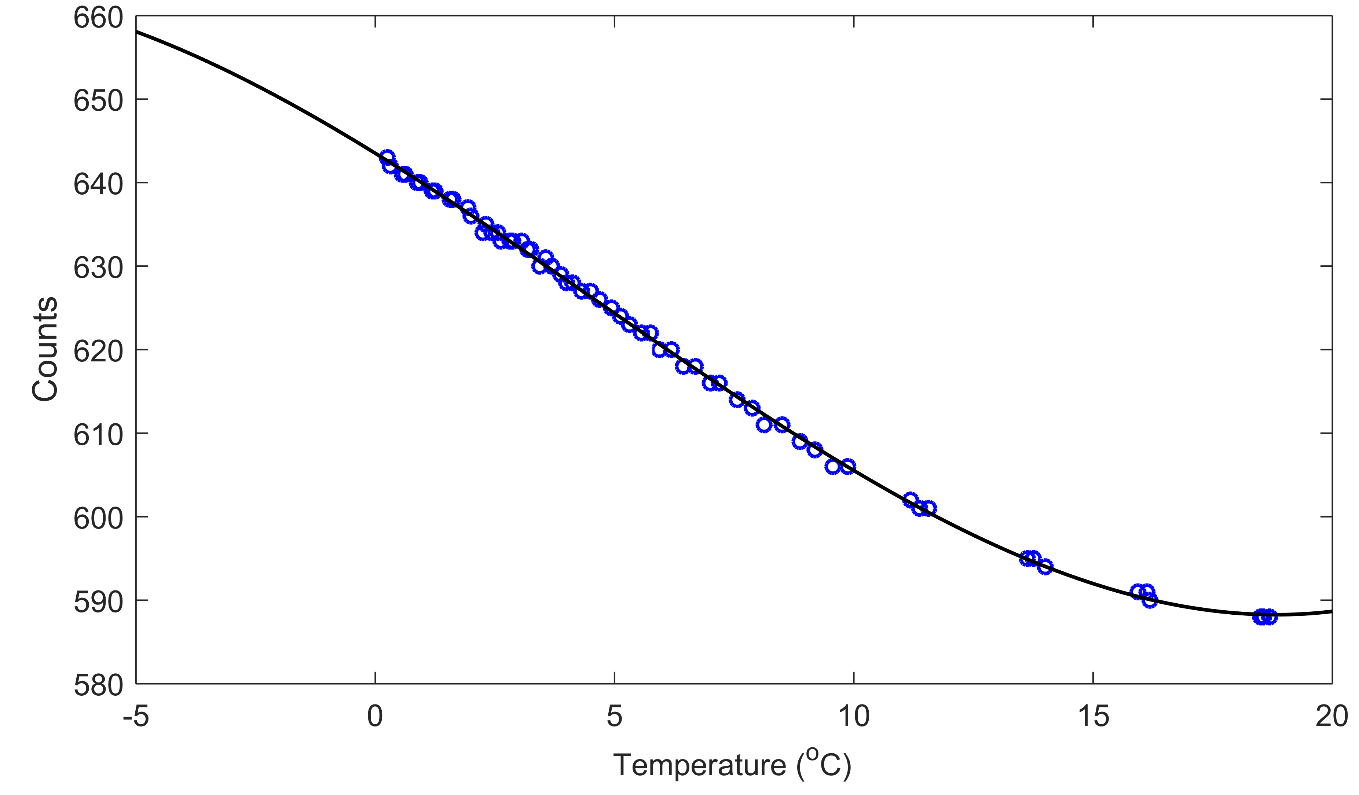
The exposure times determined were designed to be on the order of a second during the flight; however, there was some uncertainty with the final determined exposure times. The radiances used from the SASKTRAN-HR model were scalar since the vector model was still in development. ALI is a polarized instrument 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.

## 3.6.2 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 determine 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

|  |  |
| --- | --- |
|  | (3.42) |

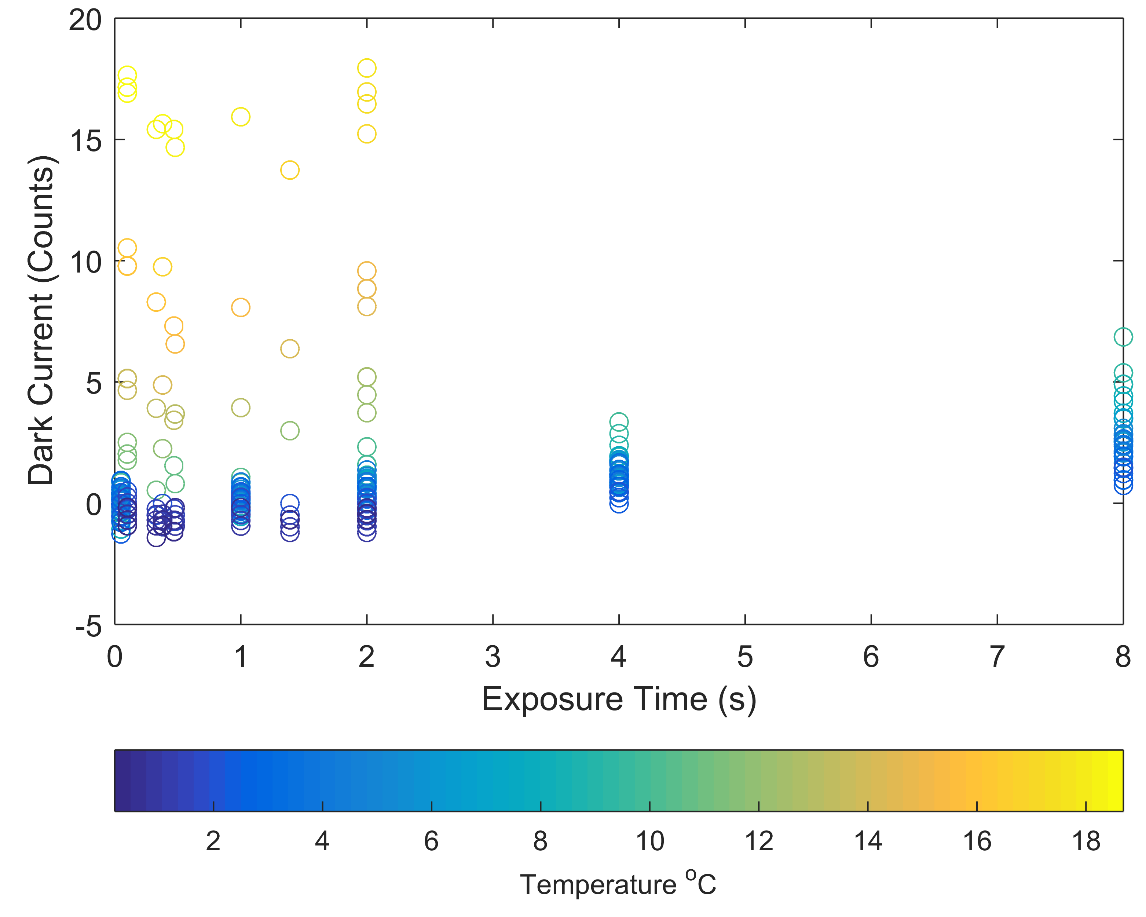
where is the temperature of the detector in degrees Celsius and is plotted in Figure 3-30.



**Figure 3-30**: The DC offset curve (Equation 3.42) 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.

## 3.6.3 Dark Current Correction

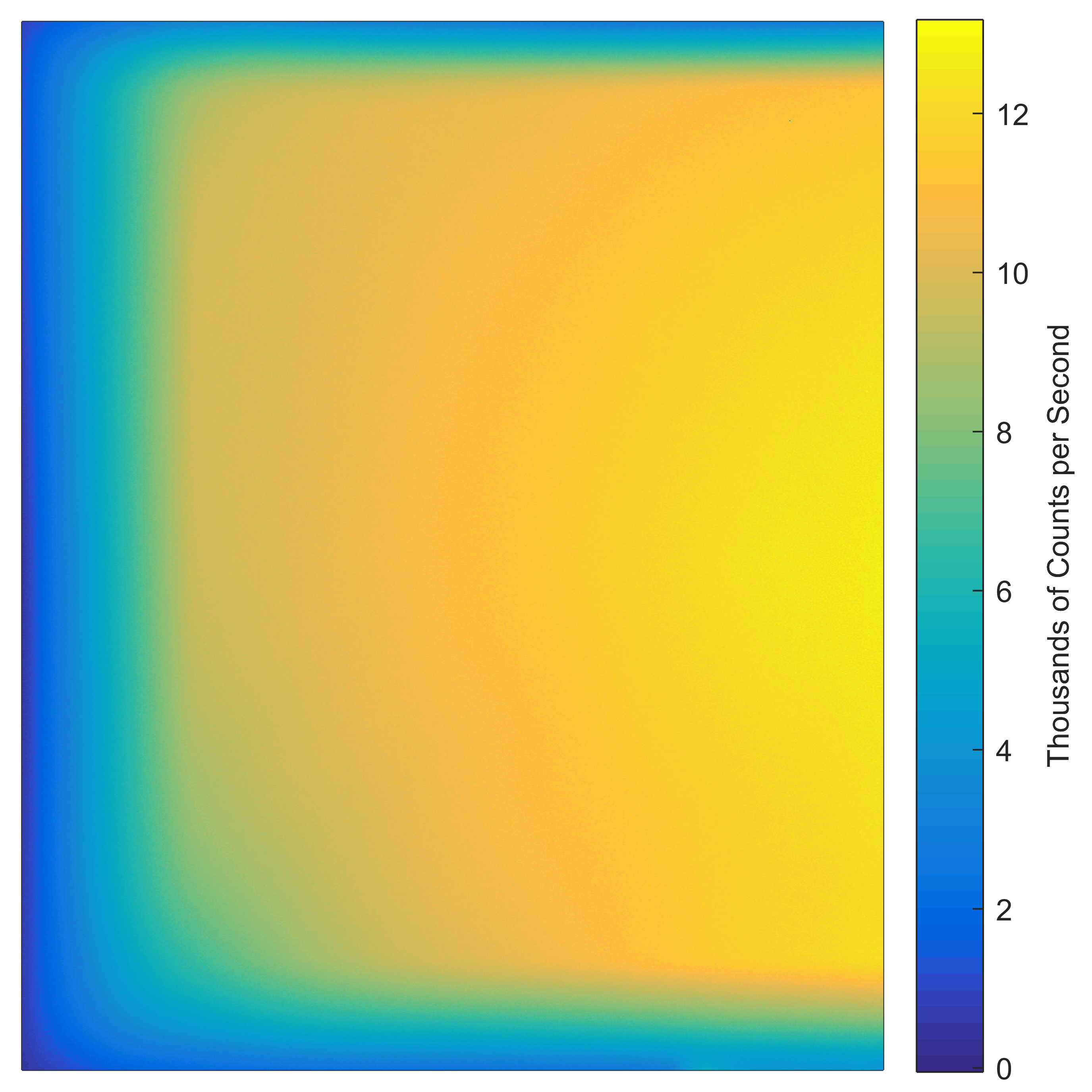
The dark current is thermal energy that builds up in the CCD detector. It grows linearly with exposure time and nonlinearly with temperature. By using images taken in darkness with a variety of exposures time, the dark current can be determined by looking at the residual after the DC offset has been removed using the curve developed in the previous section. The residual of the counts for the calibration dark image can be seen in Figure 3-31. During the campaign, the operating temperature of the camera was less than 10oC throughout the entire flight and most exposure times were less than five seconds (shown in blue) leading a very small dark current contribution in the measurement images. 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.



**Figure 3-31**: The dark current from the calibration images over a series of camera temperatures and exposure times.

## 3.6.4 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 field of view. The second is internal stray light, which is caused by scattering, reflections or other imperfections in the optical elements. As mentioned above, stray light removal is critical for limb scatter measurements.



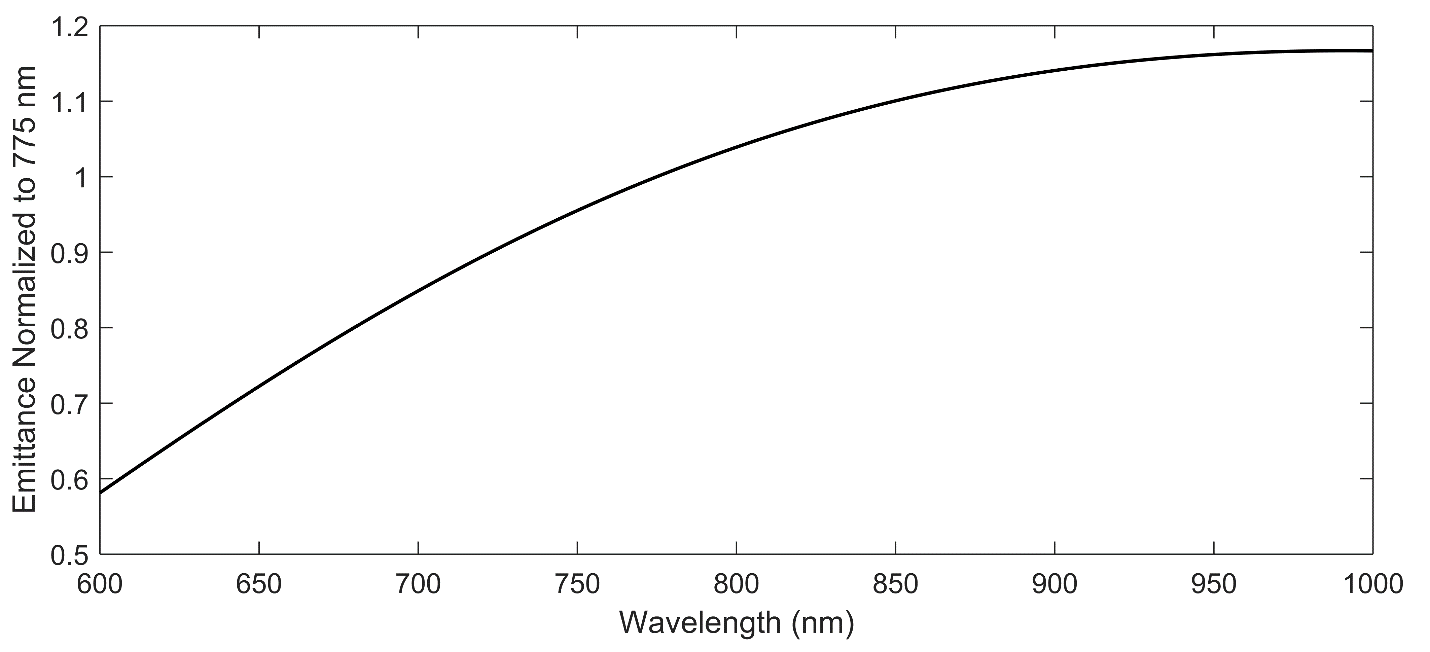
**Figure 3-32**: A calibration image after stray light removal has been performed where the measured wavelength is 750 nm with a 1 second exposure time. Vignetting can be seen as moving away from center of the image. Additionally the last 1o of the horizontal field of view is on the right side is lost 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 characteristic, 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 **3-32**. 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.

## 3.6.5 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.

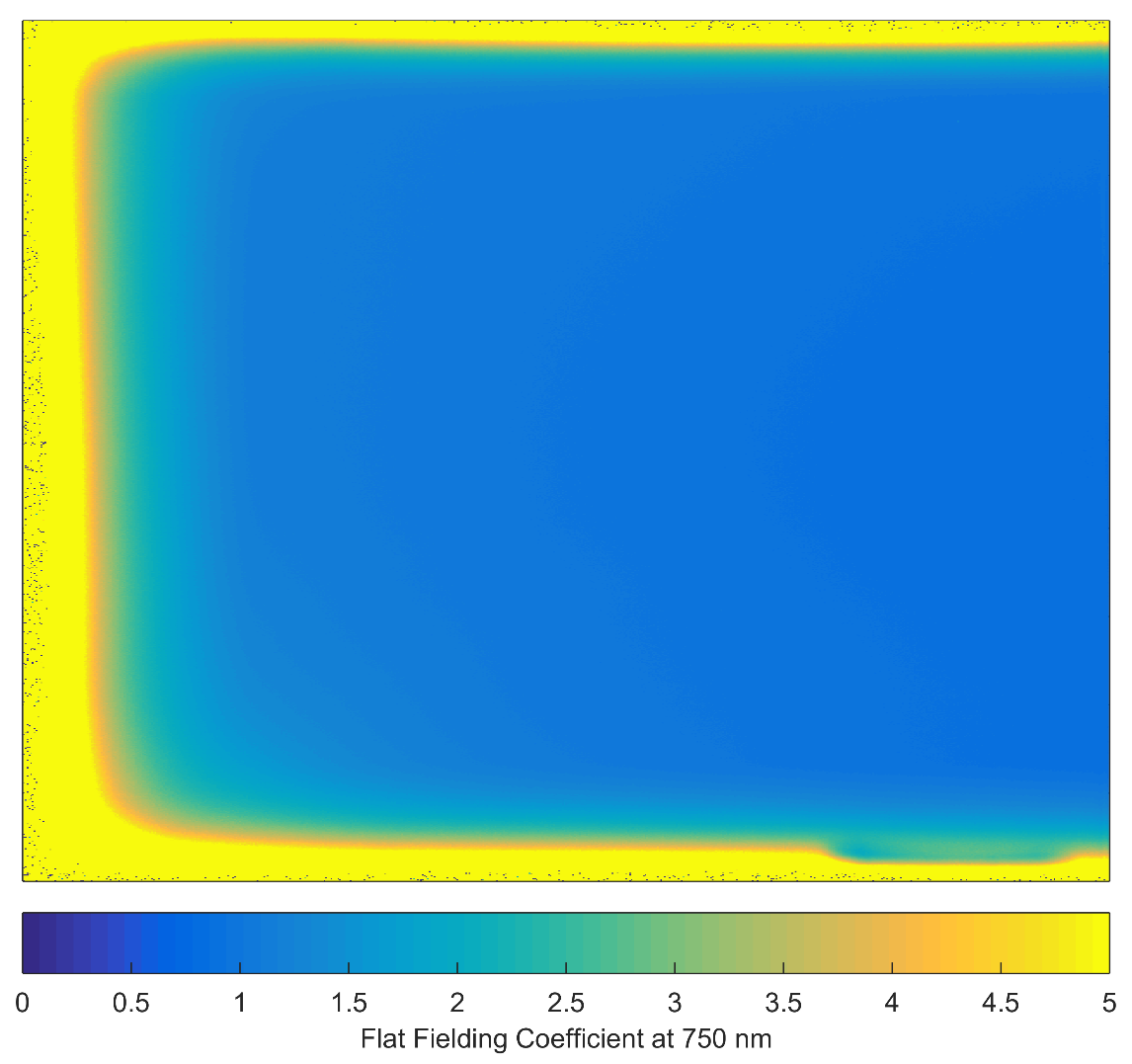


**Figure 3-33**: The blackbody emittance curve from Equation 3.43 normalized to 775 nm.

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

|  |  |
| --- | --- |
|  | (3.43) |

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 3-33.



**Figure 3-34**: The flat fielding coefficients for 750 nm.

An example of the flat fielding coefficients for 750 nm can be seen in Figure 3-34. A majority of the coefficient for the central FOVs are near unity which should 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 field of views. 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.

## 3.6.6 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. 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. 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 gondola’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.

The full integration testing occurred on August 12, 2014, along with a second instrument, the OSIRIS development model (*Kozun* 2015; *Taylor*, 2015) which was flown alongside ALI during the Timmins campaign. 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 systems 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 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.

1. Portion of sections 3.2.3, 3.2.4, 3.3.3, 3.6.4, and 3.6.5 as well as Figure 3-4, 3-5, 3-7, 3-18, 3-22, and 3-32 were originally published in *Elash et al.* (2016) [↑](#footnote-ref-1)