CHAPTER 3

INSTRUMENT DESIGN[[1]](#footnote-1)

# 3.1 Introduction

Aerosol is an important component in the climate balance and new instruments with the capability of measuring aerosol with high resolution and accuracy are required for the near future. These instruments will need to have the ability to determine both aerosol concentration as well as particle size information to better understand the effect of aerosol on the global climate. This chapter discusses the ALI instrument with the goal of measuring high quality aerosol profiles to fulfill the need of future scientific monitoring. The design of ALI is covered from the initial planning to the completed optical and opto-mechanical system. 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. 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

# 3.2 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 wide acceptance angles. This section discusses the theory behind the AOTF.

## 3.2.1 Solution to the Acoustic Equation

The 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 an AOTF in a precision optical instrument, it is imperative to understand the detailed principle of operation. The AOTF produces 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 diffraction regime which will be assumed for this derivation. Understanding the interactions between the light and the sound (acoustic) 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 are represented by an incident and diffracted (or filtered) electric fields and the third is a sound wave that is generated by an applied Radio Frequency (RF) wave. Solving the AO wave equation for an AOTF will determine the form of the incident and diffracted waves in terms of optical and medium parameters. This is useful to determine the primary characteristics 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 of the AO wave equation.

The derivation starts with the determination of the AO wave equation starting from 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 is the change in 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 differ. Using this standard, the susceptibility is given by 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 acoustic wave. As mentioned earlier a solution for this equation is presented in the Bragg region meaning only first order diffraction effects are considered.



**Figure 3-1**: Geometry for the AOTF wave derivation assuming the acoustic wave is along the x-axis and the AO interaction occurs along the z axis over an 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 most wave fronts 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 angular frequencies and wave vectors for the incident and diffracted beams. The modulation caused by the acoustic wave is a strain on the crystal given as

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

where is the angular frequency of the RF wave, and is the acoustic wave vector.

Equations 3.5 through 3.7 are used to determine the coupled wave equations by using them in the acoustic 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 term needs to be very small or equal to zero ( *i.e.* ) for the previous coupled equations to have a useful solution. The momentum matching criteria is an important result and will be used to find the tuning curve and diffraction angle within the AOTF. For efficient Bragg diffraction, the geometry is set up such that the difference of the wave vectors for the incident electric field is small or zero. Finally, and are 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 a function of the inverse of wavelength. It should be noted that the angular frequency of the diffracted wavelength is through 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.

## 3.2.2 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”-squared function shape for the spectral Point Spread Function (PSF) of an AOTF. The PSF describes the spectral bandwidth of the filtering capabilities of the device and is the limiting factor of the spectral resolution of the AOTF. For ALI, this limit must be sufficiently small enough (approximately less than 10 nm) to be able to accurately resolve aerosol from atmospheric measurements. Additionally, 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 assumes the interaction occurs 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 useful 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 efficiently 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) |

Thus, the efficiency of the diffraction at a wavelength, , can be optimized 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 the RF wave should be large enough to drive the argument of the sinusoid function in Equation 3.18 towards . It should be noted that increasing the RF power beyond a certain limit can have the possibility of deceasing the AOTF diffraction efficiency (*Xu and Shroud*, 1992).

## 3.2.3 Diffraction Angle

Although the wave equations are useful in determining the diffraction efficiency, PSF, and the form of the electric fields, these relations do not determine two useful and practical parameters: the angle of the diffracted wave, and the relation between the acoustic wave frequency and the diffracted wavelength, known as the tuning curve (covered in section 3.2.4). Instead the momentum matching criteria realized through Equations 3.8 and 3.9 are used.

The diffraction angle is analyzed using the interaction between the acoustic sound wave and the light wave 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 acoustic wave within the crystal is given by . It is assumed that the extraordinary light undergoes the momentum matching through the device.

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



**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 acoustic 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.

An important consequence of this relationship is that the diffracted light leaves the AOTF at a different angle depending on the RF. This translates to angular movement of the diffracted beam as the filtered wavelength is scanned. In order for the device to be usable in an imaging optical system, the diffracted light should leave the device following the same path independent of selected wavelength. 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.

## 3.2.4 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 a tellurium oxide (TeO2) crystal in a birefringent orientation where is the propagation angle of the acoustic wave with respect to the crystal orientation.

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) |



**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 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 approximated as

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

assuming difference in indices of refraction is small (Equation 3.28) (*Voloshinov and Mosquera*, 2006). This equation has several implications to the operation of the device that affect 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, or diffracted, wavelengths. Also, through the described interaction, the diffracted light goes through a 90◦ rotation in polarization (*Voloshinov*, 1996). Finally, 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 ◦C for TeO2. This theory of AOTF operation provides the foundation to utilize the device in a spectral imaging system for limb scatter measurements of stratospheric aerosol.

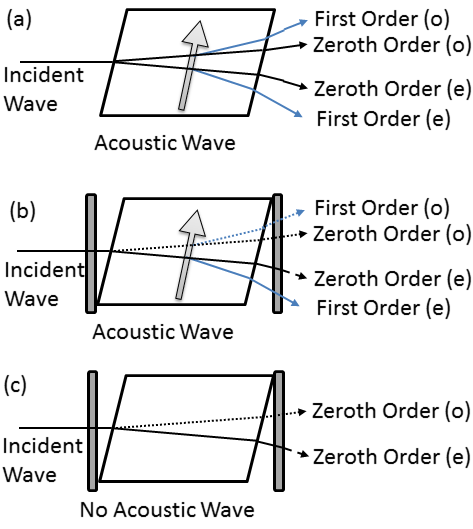
# 3.3 Optical Chain Development

The ALI design goal for the stratospheric balloon prototype presented in this work is a simple optical system with commercial off-the-shelf components that is capable of imaging the stratospheric limb a single wavelength at a time through the use of an AOTF. However, the AOTF operation requires important instrument design considerations to optimize its operation and performance (*Suhre et al*., 2004). First, a brief overview of AOTF operational states is discussed. Then an introduction to the two optical design layouts considered for ALI is presented followed by an overview of the finalized ALI optical design. The final design as built is capable of imaging the stratospheric limb with a spatial resolution of 200 m for both vertical and cross-track dimensions over the wavelength range of 650-950 nm. This range is slightly smaller than the original specifications and is a consequence of the usable range of the chosen detector due to quantum efficiency limitations. 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 AOTF Operation

This section describes the two fundamental states of the AOTF used throughout the rest of this work but first is the general operation of the device itself. The general operation of the AOTF is shown in Figure 3‑5a. An RF wave is applied and 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 90◦. Further, only the first order extraordinary polarization remains at a consistent angle as the RF is scanned due to the compensation mentioned in section 3.2.3.

In practice, the first order extraordinary beam is imaged and the removal of the unwanted beams is 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 placed 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 with only the first order extraordinary wave passing through the system. 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 with no outputs from the system. These two states, “AOTF-on” and “AOTF-off” are used throughout the remainder of this work to describe these two operational modes of the system.



**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).

An AOTF for the ALI prototype was acquired from Brimrose of America (model number TEAFI10-0.6-1.0-MSD) with a DC-powered Gooch and Housego RF driver (model number 64020-200-2ADMDFS-A). This particular AOTF has a large 10 mm by 10 mm aperture and is an imaging quality crystal. It is tuned for a spectral range of 600 nm to 1200 nm, which corresponds to an RF range of 156 to 75 MHz. The spectral resolution is approximately 1.6 nm at 633 nm and broadens to about 6.3 nm at 1153 nm with an approximate diffraction efficiency of 60% across the spectral range. The AOTF is made from a tellurium dioxide (TeO2) birefringent crystal. The extraordinary light is diffracted at 2.7◦ from the optical axis of the device with a minimum separation angle of 6.4◦ between the zeroth and first order. The acceptance angle is 2◦ from the normal, which defines the angular spread of the incident beam for which the AOTF provides diffraction within the rated efficiency limit (*Xu and Shroud,* 1992). A detailed overview of the AOTF specifications can be found in appendix A.1.3.

## 3.3.2 Telecentric System Prototype

The first optical system considered for ALI is a telecentric system, which is known as a system that images without perspective. Before the telecentric design is discussed a basic explanation of a telecentric system is provided.



**Figure 3-6**: 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 3-6 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 the system has infinite depth of field. However, an aperture that is so small proposes a few problems in practice. First, 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 to meet the required Signal to Noise Ratio (SNR). 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 the image 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 3‑7**: 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. (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 as shown in the ray tracing diagram (Figure 3‑7), all lines of sight enter with approximately the same angular spread, so the filtered image has constant wavelength and spectral point spread function across the image plane. However, two problems result with this system. First, the focus of the final image depends 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 telecentric Front End Optics (FEO) in both object and image space and with Back End Optics (BEO) designed to resize the image to fit on a CCD detector. 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 3‑7. Here the AOTF optical aperture of 10 mm by 10 mm is the field stop of the system. This is obviously a physical limit of the device and causes the Field Of View (FOV) to be limited in this design. In order to image the vertical limb from the ground to float altitude of a stratospheric balloon, typically 35 km, a 6◦ FOV is required. Also, using standard 100 mm focal length lenses, the rays of light from each line of sight enter the AOTF at the maximum acceptance angle, which is 2◦. 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 (◦) | 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 3-8.



**Figure 3-8**: Quantum efficiency of the Kodak KAF-1603ME contained within the QSI CCD camera is represented by blue curve. Quantum efficiency provided by QSI Scientific. (http://www.qsimaging.com/616-overview.html)

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 wavelength and have the similar spectral PSF.

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)

|  |  |
| --- | --- |
|  | (3.33) |
|  | (3.34) |

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

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

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 3-9. 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.



**Figure 3-9**: 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.

The severity of this problem can be seen in Figure 3-10 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 was passed through the system for each FOV and using ray tracing the final location for each FOV on the image plane were 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 3-10**: 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 3-11. The experimental set up was similar to the system in Figure 3‑7 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 was removed by adding a polarizer before and after the AOTF (Figure 3‑5b and Figure 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 90◦ 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 3.2.4, the polarization of the diffraction beam is rotated by 90◦ (*Voloshinov*, 1996). The second issue to be handled is that the AOTF bends the optical path by 2.7◦. 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 which then obscures a small part of the FOV. 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, every 25 nm at wavelengths between 600 and 1000 nm using 30 second exposures imaged on the QSI CCD camera. The “AOTF-off” image was subtracted from the “AOTF-on” image to approximately remove the detector dark current, DC offset, and stray light. Three sample images can be seen in Figure 3-11 with the optics focused at 800 nm. The image blurring that was simulated in the spot size diagram can be easily noticed in the 650 nm wavelength image. At this wavelength the center lines of the resolution chart cannot to be resolved from each other. A unique line 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 decreased reflectivity of the chart at the longer wavelengths of light, the SNR of the 850 nm image in the bottom right panel is rather low; this can be observed in the grainy quality of the image.



**Figure 3-11**: The top left is the original test image used for the telecentric 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.

## 3.3.3 Telescopic System Prototype

The second optical system layout considered for the ALI prototype is a telescopic optical system configuration consisting of a standard telescope for the FEO with a focusing lens for the BEO. 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 3.3.2. A detailed simulation Code V layout and ray tracing of the optical design can be seen in Figure 3-12.



**Figure 3-12**: 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. (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 3‑7. 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.



**Figure 3-13**: Vertical displacement of a collimated bundle of light cause by a material of index of refraction .

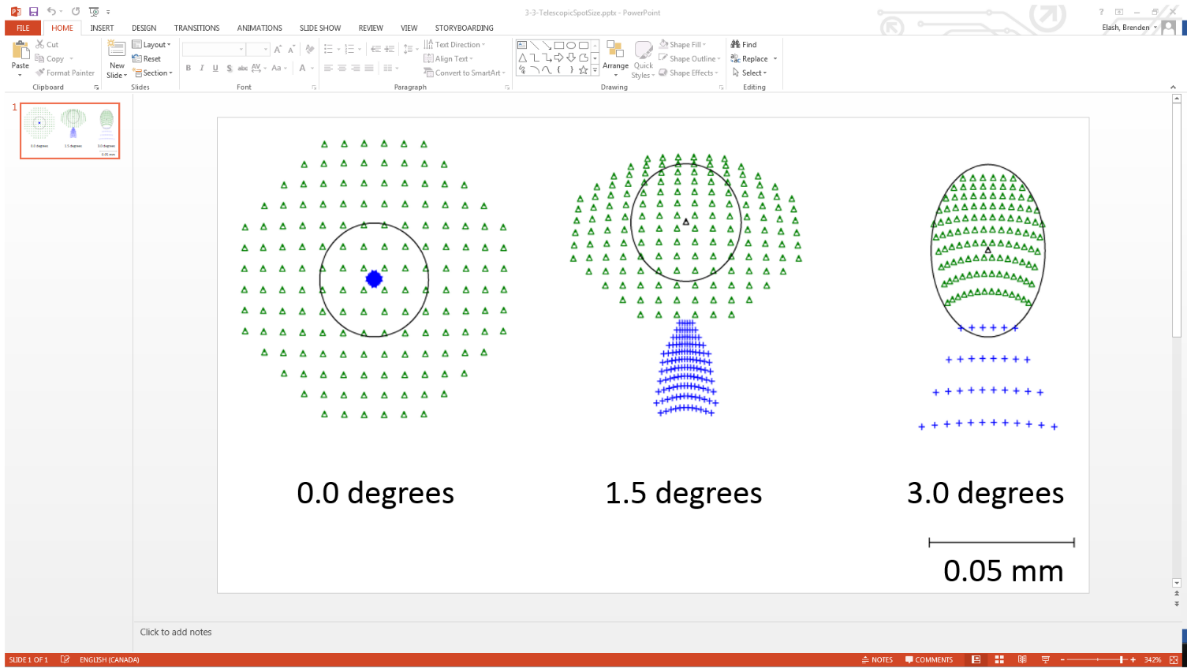
**Table 3-2**: Telescoptic Prototype System Optical Parameters.

|  |  |
| --- | --- |
| Parameter | Value |
| Effective focal length (mm) | 75.6 |
| Front End Optics Magnification | 1.00 |
| Back End Optics Magnification | 0.756 |
| Field Of View (◦) | 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 impacts that both improve and degrade the imaging quality of the system. First, the primary light passing through the AOTF from a single line of sight enters 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). Thus 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 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 (*Fischer et al.*, 2008)

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

where is the displacement from the original path and is the thickness of the material; 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 at worst 50 micrometers for the test configuration. The effect can be seen in Figure 3-13. The last change to the system is the focusing power it possesses, as can be seen in the spot diagrams in Figure 3-14. The change in spot size due to wavelength is primarily due to the chromatic aberrations of the optical lenses. If it is desired to remove the chromatic aberration one option is to replace the lenses with mirrors in the flight version, the second option is to use achromatic doublets. 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 3-14**: Code V simulation of the spot size for the telescopic system. The spots are shown for 0.0, 1.5 and 3.0◦ 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 3.0◦ 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 assembled with the telescopic system with two polarizers and prisms added to the optical chain in the similar fashion to the section 3.3.2 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 3-15. 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 detector efficiency and the resolution target’s poor reflectivity in the NIR causes the 850 nm image to also have a low SNR.

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

**Figure 3-15**: The top left is the original test image used for the telescopic 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.

## 3.3.4 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 (ThorLabs model number LPVIS100, see Appendix A.1.2) 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 90◦ rotation in polarization so a second linear polarizer, oriented at 90◦ 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. This unabsorbed signal, if not mitigated, can significantly reduce the instruments sensitivity to the desired signal.



**Figure 3‑16**: 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 2.7◦ 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 the ALI optical system was created using the Code V optical design software and can be seen in Figure 3‑16. No corrections were attempted to reduce chromatic or spherical aberrations within the system and the system does exhibit some coma due to a large FOV and the curvature of the lenses near the edge of the FOV. Analysis with Code V shows that the distortion due to these effects across the center two degrees of the FOV is a change of less than 1% across the entire wavelength range. The final one degree shows a distortion of less than 4%. Finally the lateral displacement in the telescopic test configuration has been reduced in the final design to be on the order of a micrometer and is considered negligible.

An analysis was also performed to determine the minimum resolution required to achieve a Modular Transfer Function (MTF) of 0.3 across the entire FOV 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, increasing line pairs per millimeter leads to a circumstance where the system can no longer resolve the lines. The MTF can be found computationally through (*Fischer et al.*, 2008)

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

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 3◦ tangential or perpendicular FOV, a seven pixel running average is required, corresponding to a MTF frequency of 15.5 line pairs per millimeter. The 3◦ 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 2.7◦ from the normal the tangential component is above the 0.3 MTF threshold. The MTF analysis of ALI can be seen in Figure 3-17. Overall, this corresponds to an average vertical and horizontal resolution of 210 m across the entire ALI FOV at the tangent point.



**Figure 3-17**: MTF analysis performed by Code V for the final ALI design used in the balloon 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 (◦) | 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 |

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, the Code V analysis 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. It was found that the ALI design was relatively insensitive to the tolerances of commercial off-the-shelf component used.

An experiment to determine the exposure times and entrance pupil of ALI is discussed in detail in the calibration section of Chapter 4, but for design purposes it is important to note here that the ALI entrance pupil was selected at 9.91 mm to yield estimated flight exposure times on the order of one 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 also important to note that a detector could not be acquired with sufficient capability to capture the entire desired range 600-1200 nm due to basic limitations of silicon technology. This required a reduction in the desired spectral range to 650-950 nm. Although high quality aerosol extinction measurements can still be made with this spectral range as evidenced by the OSIRIS data product heritage this limitation means that the ALI prototype does not have the desired sensitivity to particle size distribution. However, even with this spectral range some particle size information can still be retrieved as evidenced in Chapter 5.

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). Even 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 FOV 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 FOV 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 ALI, the telescopic system was deemed to be the better option for the purpose of dedicated measurements of aerosol extinction.

## 3.3.5 Correction to the Optical Design

It should be noted a correction to the optical design is required that was discovered during the analysis of the data after the instrument campaign. The 3◦ half-angle FOV signal enters the AOTF at an angle of 2.2◦ from the normal and the acceptance angle of the AOTF is 2.0◦. This results is a great loss of diffraction efficiency for approximately the last half degree of the FOV. 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 in the last half degree of the FOV 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 is in regard to the front end magnification and the suggested solution revolves 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 3‑16) by 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 3◦ half-angle FOV entering the AOTF at 1.6◦ well within the acceptance angle of the AOTF. A table of the revised specifications can be found in Table 3-4.

**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 (◦) | 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 |

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 overall but the last half of a degree of the FOV 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 is reduced in size which should decrease the resolution of the instrument. However, the decrease is partially offset by the larger f-number which reduces the system aberration thereby resulting in a final average vertical and horizontal resolution of 260 m.

# 3.4 Opto-Mechanical Design and Thermal Balancing

Upon the finalization of the optical design of ALI, an appropriate opto-mechanical and thermal system was required for test flight on a stratospheric balloon. This section gives an overview of the hardware used to transform ALI from a laboratory breadboard to a flight model prototype. The opto-mechanical design section discusses the optical mounting approach 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 in the system and how the prototype was designed to minimize the thermal risks.

## 3.4.1 Opto-Mechanical Design

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 experienced during the flight in order to keep the optics in the system aligned and in focus. Furthermore, the system had to also meet safety factors for torque and shock forces on the instrument so that it ould not become detached from the gondola during the flight. These strict regulations were in place 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 choosing materials to house the optical lenses housing system in order to reduce the chance of any torques arising in the optical chain from thermal expansion. 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. The chosen material was aluminum since it is commonly used in space-based instruments and platforms because of its strength, light weight, and relatively inexpensive cost.

Housing of the optics also required some consideration. Commonly, space-based instrumentation uses a solid piece of material that is machined into the shape required and weight-relieved by machining contours into the surfaces. However, this method is relatively expensive and not within the budget for this prototype project. The most sensible 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 at relatively low cost. Some particularly challenging mounting issues were tackled with small custom machined parts. The drawback, or trade-off, with only using off-the-shelf components is that it is more difficult to guarantee and maintain the alignment of the system.

Using components from ThorLabs, Edmund Optics, Newport, and McMaster-Carr, an opto-mechanical case and mounting system was designed for the ALI prototype. The optical rail system is shown in Figure 3-18. A single sturdy wide optical rail, element 11, was used as the system base since it has the whole optical chain plus a baffle (discussed in section 3.4.2) mounted to it and would have a low susceptibility 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 3-18. Once the aligning of the optical system was completed, the components were glued into place with a suitable epoxy to prevent slippage during transportation and launch.

During the testing of the breadboard optical system in the lab, two prisms were used to account for the deviation in the optical chain caused by the AOTF. These prisms were removed in the final design by bending the BEO of the optical chain by 2.7◦ through a rotation stage (element 7). The removal of the prisms further reduced distortions within the system as mentioned in section 3.3.4.

It should be mentioned that optical lenses for ALI were selected for the final system with the addition of antireflection coatings. The coatings increased the systems efficiency as well as reduced internal reflections. 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 were 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 procure and greatly limited the possible choices. A nanoparticle linear film polarizer from ThorLabs was eventually selected (model number LPVIS100, see Appendix A.1.2) since it has an extinction ratio better than 105 for 650 to 1200 nm, completely covering the operating range. The extinction ratio is defined by the ratio between the maximum transmission when the polarizer’s axis is aligned with a linearly polarized incident signal to the maximum transmission after the polarizer has been rotated by 90◦.



**Figure 3-18**: 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.



**Figure 3-19**: 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.



**Figure 3-20**: 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).

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 pre-existing components could be purchased to mount these pieces. Therefore custom mounting hardware had to be used to rigidly mount these components. Both components were designed through the use of the SolidWorks design software and can be seen in Figure 3-19.

The ALI system was tilted three degrees from the horizontal so that the symmetric 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 3-20.

Finally, mounting hardware was tested through stress analysis calculations done by the CSA to verify that the safety factor of the system was met. ALI passed all safety requirements for the stratospheric balloon launch.

## 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 FOV. 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 determined. 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.

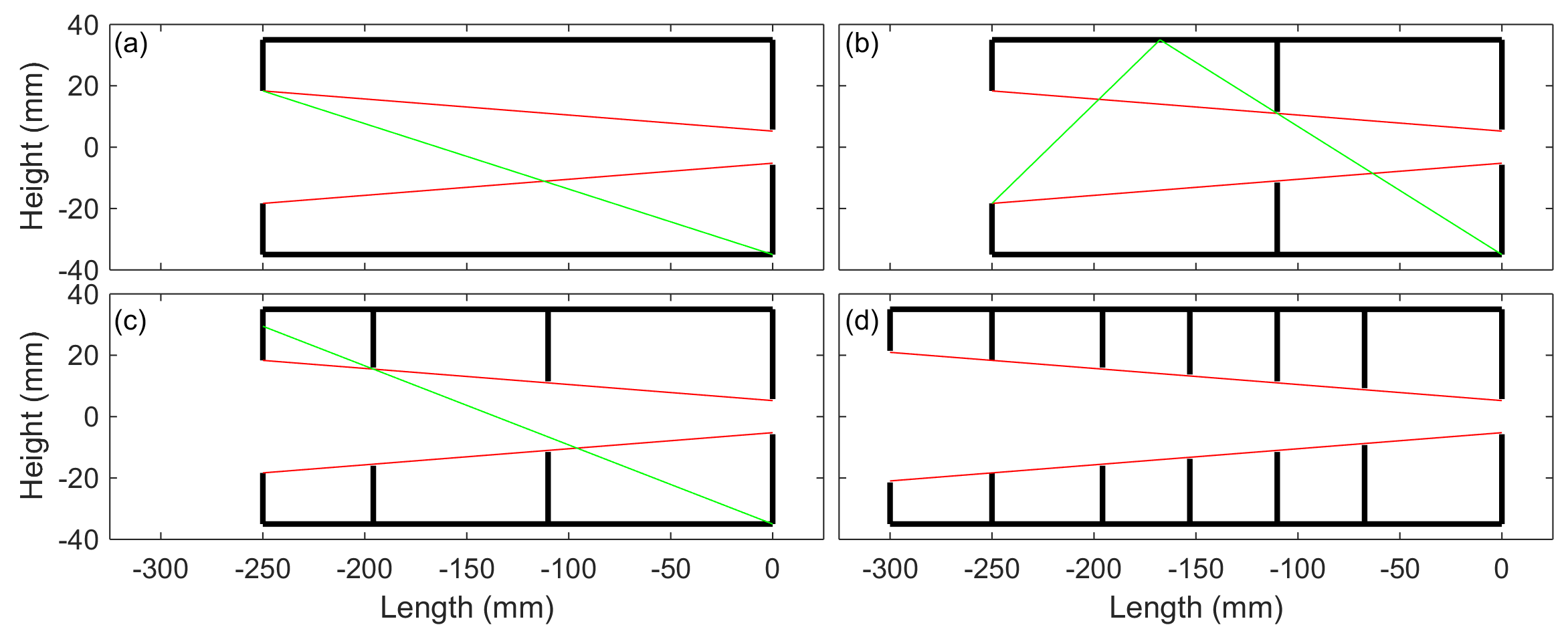
The first point of the discussion is the height and width of the baffle. In a baffle system, the larger the baffle is by cross-sectional area the better the baffle can be designed to reduce stray light. However, there is a limited amount of space to build the ALI instrument and the baffle must share 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 FOV and entrance aperture size. The baffle must be short enough so that the size of the FOV 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. This length is 300 mm with 250 mm for the primary baffle and 50 mm dedicated for an external baffle to reduce surface reflections.

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 FOV 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. In the other case, the optical stop is moved closer to the optical system and the opposite problem occurs. 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 a standard used in optics to minimize stray light (*Fischer*, 2008). In the system, the baffles are spaced in such a way that little stray light cannot enter the system without coming into contact with at least three scattering surfaces thus reducing the overall intensity of the stray light.

The optimal baffle geometry design method is described here. In Figure 3-21a, 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. The marginal rays of the optical system are represented by the red line.



**Figure 3-21**: (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 baffles 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 intersects, and has been added in Figure 3-21b.

The next indicator line goes from the bottom corner to just passing the newly inserted 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 3-21c.

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 has been achieved. However, two extra internal baffles and one external baffle were added to the design (Figure 3-21d). 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 (*Fischer et al.*, 2008)

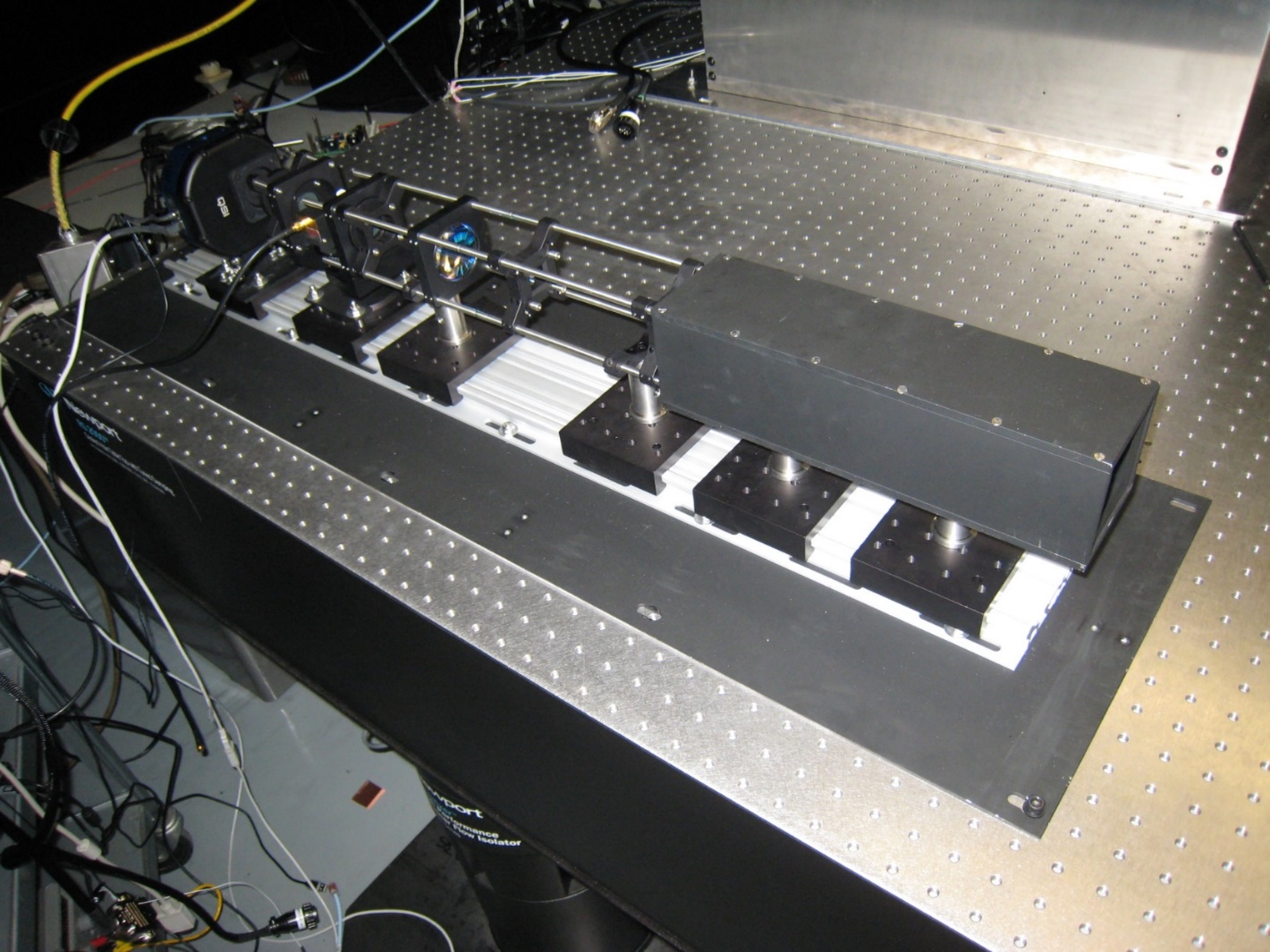


**Figure 3-22**: A cross-section view of the ALI baffle system. All dimensions on the drawing are in millimeters and the sloped black lines represent the 6 degree FOV.



**Figure 3-23**: ALI baffle vain profile. Dimensions are in millimeters.

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 3-22 which accounts for the thickness of the materials and machining tolerances.

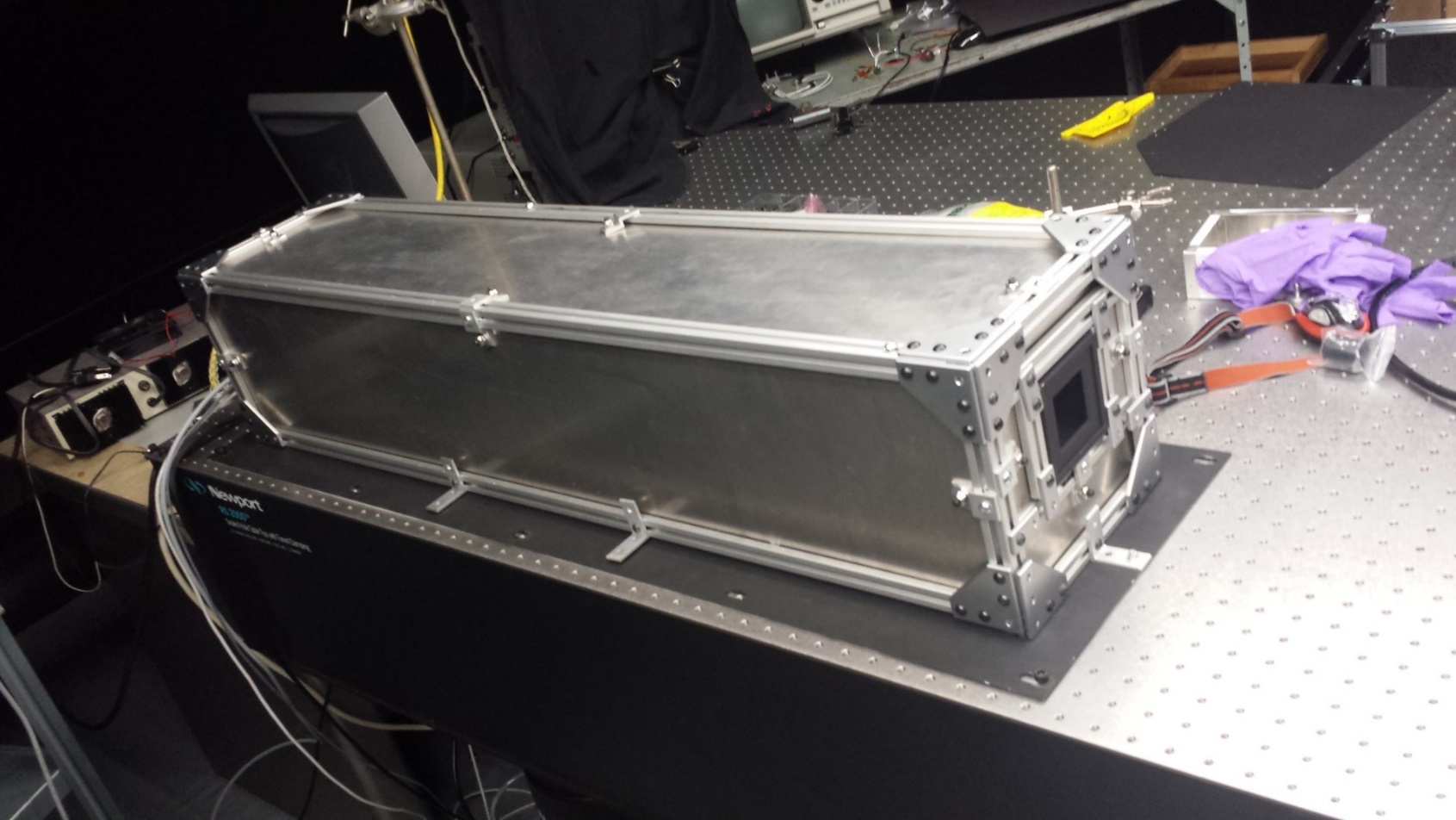


**Figure 3-24**: Final ALI optical and opto-mechanical assembly.

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. Figure 3-23 shows the profile for the baffle vanes as they were machined. A final assembly of the optical system can be seen in Figure 3-24.

## 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 ensure the rejection of all light. The light tight case was clamped onto the base plate of ALI and a photograph of the finalized prototype can be seen in Figure 3-25.



**Figure 3-25**: 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, had to survive the possibility of extreme temperatures during the flight on a stratospheric balloon. The extreme temperatures could arise though various processes. First the instrument must survive the ascent through the tropopause where temperatures can reach -70◦C and must survive the float temperatures which can be as cold as -50◦C. Conversely, being exposed to direct sunlight causes heating that would result in instrument failure due to overheating. Furthermore, since simple opto-mechanical design were used for ALI there was no active thermal control. With the reduced atmospheric density at approximately a float altitude of 35 km, convective cooling could not be relied upon for thermal control. The following is a discussion of various thermal concerns within ALI.

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

However, the RF driver does not fall into the specified temperature range, which was a problem. In addition the driver also produced a large amount of heat that was convectively cooled in the laboratory which was not possible at float altitude due to the reduced atmospheric pressure. Since the RF driver was a fundamental piece of hardware, failure in the component would result in a primary system failure.

To mitigate the risk, several considerations were made with regards to the RF driver. First, a RF driver with a cooling plate was purchased to better allow for conductive thermal control. The driver was mounted in thermal contact with the aluminum case such that the cooling plate was in direct contact with the surface of the case, which was then mounted directly against the aluminum mounting surface on the gondola. This allowed a large amount of heat to be conducted to the gondola to keep the RF driver within the operating range. Reaching too cold of a temperature was not as large of a concern since the driver produced enough heat to sustain its operating temperature. However, as the driver was a power hungry component it was desirable to toggle the power to save battery. In this case, overcooling of this component was a concern. A temperature sensor was used to monitor the driver and the control software was designed with a safety measure such that it would automatically turn the driver off if it reached 50◦C or turn it on if the temperature dipped below 0◦C.

Another region of concern was the housing of the optical system which would be directly exposed to the elements. The optics can expand and contract based on the temperature. Additionally, the CCD camera had an operating temperature range of -40 to 20◦C. Furthermore, the CCD primarily used convection to cool the camera, which was disabled for flight as they would self destruct 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 that is standard for stratospheric ballooning. First, the optical housing was surrounded in foam to thermally insulate it from the cold experienced during darkness and ascent though the tropopause. Second, the foam insulation was covered in a reflective material to reduce direct warming from the radiation from the sun. The small amount of heat generated by the camera within the insulted box was enough to maintain a relatively small temperature swing of the optical chamber during the flight.

1. Portion of sections 3.3.1, 3.3.2, 3.3.3, and 3.3.4 as well as Figure 3-4, Figure 3‑5, Figure 3‑16, and Figure3-20 were originally published in *Elash et al.* (2016) [↑](#footnote-ref-1)