CHAPTER 3

OPTICAL DESIGN AND CALIBRATIONS

This chapter will discuss ALI from the initial planning to a completed system including calibration and testing. First, a discussion of the Acousto-Optical Tunable Filter (AOTF) will occur that covers the solution of the wave equation, diffraction efficiency, diffracted angle output, and tuning curve. Following is a calibration of the specific AOTF used in ALI. With the completed characterization of AOTF, discussion of the two primary optical layouts considered for the instrument with the final design and optical specifications will be presented. Next, the system will be tested as a whole and finally an outline of addition components will be addressed.

# 3.1 AOTF Theory and Background

The fundamental piece of technology that allows for the building of ALI is an Acousto-Optical Tunable Filter (AOTF) which permits a signal to be passed through a band gap wavelength filter. 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 qualities over a wide acceptance angles. This section will discuss the theory behind the AOTF.

## 3.1.1 Solution to the Acoustic Equation

An AOTF is a device that through phonon-phonon interactions and Bragg diffraction allows a broadband light source to be filtered into a spectral 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 of the incoming light and its propagation direction, commonly called birefringence. For image purposes, a wide aperture is required for an AOTF and has been developed (*Gass and Sambles*, 1991) and are currently readily available for imaging purposes. In order to fully understand the principles behind an AOTF a stress analysis through the acousto-wave will be used to solve the wave equation.

A derivation of the wave equation for the Acousto-Optic (AO) effect will be presented starting from two of Maxwell’s equations, Amperes law and Faradays law, seen in the following

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| --- | --- |
|  | (3.3) |
|  | (3.4) |

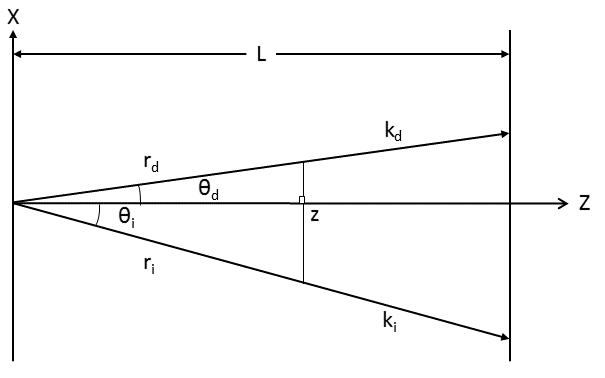
where is an electric field, is the magnetic field, is the current density, is the permeability, and is the permittivity. By taking the curl of the equation 3.3, combining it with equation 3.4, and assuming that the AOTF crystal is non-conductive (*i.e.* ) along with the identity and assuming the crystal has no net charge (*i.e.* ) gives the simplified form

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

Since the dielectric is not a constant with time it induces a susceptibility yielding the following form

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

where is the induced polarization due to the stress in the AO medium given by and the change is the susceptibility, is given by . In the previous definition 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. A solution for this equation will be 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, . , , 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, 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 will be orientated such that the acousto interaction occurs along on the z axis and the electric field entering the device will be a plane wave described by

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| |  |  | | --- | --- | |  | (3.7) | | |  |  | | --- | --- | |  | (3.5a) | |

and the diffracted electric field is described as

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

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

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

where is the frequency of the RF wave, and is the acousto wave vector.

Equations 3.6-3.9 will be used to determine the coupled wave equations. The induced polarization is given by the incident wave and the strain wave interacting in the form of . The polarization wave will in turn stimulate the diffracted electric field yielding the first half of the coupled equations in the form

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

where 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 incident wave yielding the second coupled equation

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

Solving the coupled wave equations yields the following solutions

|  |  |
| --- | --- |
|  | (3.12) |
|  | (3.13) |

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

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

Solving for the coefficients yields

|  |  |
| --- | --- |
|  | (3.15) |
|  | (3.16) |

## 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

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

This form yields the common sinc function shape for the spectral Point Spread Function (PSF) of an AOTF. However, this form can be altered to better identify how to increase the diffraction efficiency of an AOTF. The diffraction efficiency will be 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 power at which the piezoelectric transducer pumps the RF signal into the AO medium. The average energy flow of the acoustic power is defined by

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

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 will be defined is known as the acousto-optic figure of merit, , which is completely determined by the medium properties defined by

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

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

Using equations 3.18 and 3.19 and rearranging equation 3.17 yields the following for the diffraction efficiency

|  |  |
| --- | --- |
|  | (3.20) |

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 region 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 3.20 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

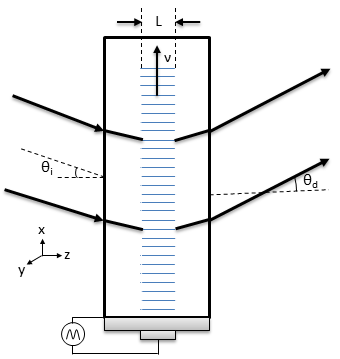
Although the wave equations are useful in determining the diffraction efficiency and the form of the electric fields; it is not convenient to determine angle of the diffracted wave or the RF acousto wave to wavelength relation known as the tuning curve (covered in the section 3.1.4). A discussion on the diffraction angle will be analyzed using the interaction between the acoustic sound wave and the phonon light by

|  |  |
| --- | --- |
|  | (3.21) |

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

|  |  |
| --- | --- |
|  | (3.22) |
|  | (3.23) |
|  | (3.24) |

It will be 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, will be used to determine the diffraction angle. Using equation 3.21, the x component of the wave vector is

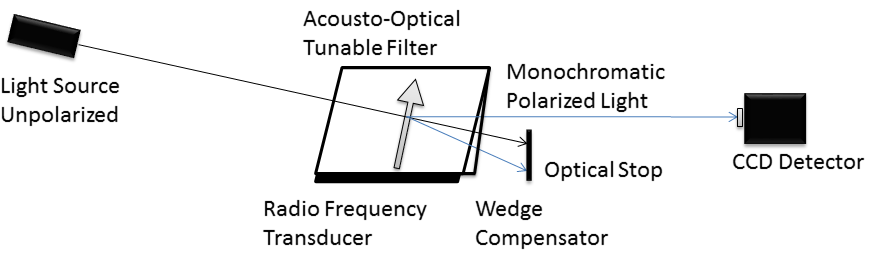
|  |  |
| --- | --- |
|  | (3.25) |

and the magnitude of the diffracted wave vector is

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

and combining the results from equation 3.25 and equation 3.26 the angular deviation of the diffracted source is

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



**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 will leave the AOTF at a different angle depending on the RF frequency which in turn alters the wavelength of light that leaves the device. 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 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 outputted diffracted light wavelength and the set acoustic sound wave frequency. The analysis will be performed using the momentum matching criteria stated in equation 3.21. 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. The indices of ordinary and extraordinary refraction for TeO2 is given by (*Uchida*, 1971)

|  |  |
| --- | --- |
|  | (3.30) |
|  | (3.31) |

for 400 to 1000 nm.

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

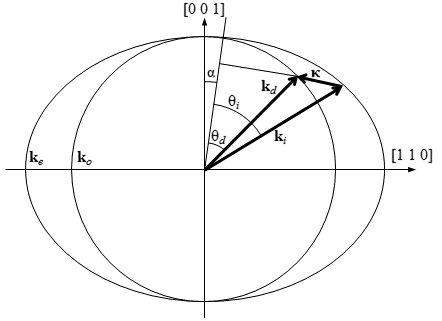
|  |  |
| --- | --- |
|  | (3.28) |
|  | (3.29) |

If the difference in the index of refraction is small, as it is for TeO2, equation 3.28 can be approximated as (*Voloshinov et al*., 2007)

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

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 3.21. Separating the wave vectors into their directional components with respect to the propagation angle, , the tangential and perpendicular directions respectively are

|  |  |
| --- | --- |
|  | (3.31) |
|  | (3.32) |



**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.

The tangential and perpendicular directions of the wave vector can be used in combination with the wave vectors definitions (equations 3.22-3.24) to yield

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

The above can be written as

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

assuming difference in indices of refraction is small (equation 3.30) 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 will result in different outgoing wavelengths. Also, through the described interaction, the diffracted light goes through a 90o rotation in polarization (*Voloshinov*, 1996).

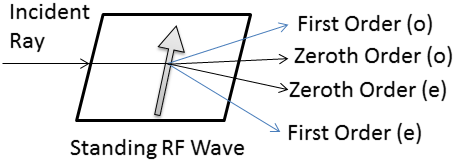
# 3.2 AOTF Calibration and Operation

An AOTF was acquired from Brimrose of America with a large aperture that is of imaging quality to be used in the ALI system. It is optically tuned for a range of 600 nm to 1200 nm and 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. A detailed overview of the AOTF specifications can be found in (TODO: ADD TO ADDENDIX LATER). First, a section on AOTF operation will be discussed and then calibration will be 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.

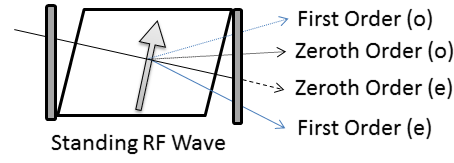
## 3.2.1 AOTF Operation

Some nomenclature with regards to the AOTF’s operational states will be defined. This section will describe the two fundamental states used throughout the rest of this work but first will be the general operation of the AOTF itself. The general operation of the AOTF is shown in Figure 3-5. In the general operation, with an RF wave applied, there is one input, the unpolarized chromatic incident ray, and four output signals. The birefringence of the crystal splits the zeroth order ordinary and extraordinary polarizations into two separate outputs. The standing 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.

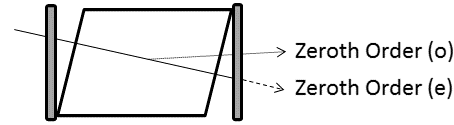


**Figure 3-5**: An AOTF undergoing Bragg diffraction with an unpolarized chromatic input with a RF wave applied represented by the arrow. After the diffraction event, four output signals are formed: the zeroth order and first order ordinary (o) and extraordinary (e) signals.

When the AOTF is used in any experiments or design, the removal of the unwanted polarizations are required to achieve high quality low contamination images. As such, a linear polarizer is always placed in front of the AOTF designed to remove the ordinary polarizations and a linear polarizer is place behind the AOTF to remove the zeroth border extraordinary polarization. When an RF wave is applied to the crystal with the polarizers, as seen in Figure 3-6, the AOTF will be consider 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 3-7, the AOTF will be consider to be in the off or “AOTF-off”state. These two states, “AOTF-on” and “AOTF-off” will be used throughout the remainder of this work to describe these two fundamental states of the AOTF.



**Figure 3-6**: An AOTF with a RF wave in the on or “AOTF-on” state. Two linear polarizers are added to the system, the first linear polarizer removes the ordinary polarization removing the outputs with the dotted lines and the second linear polarizer removes undiffracted extraordinary light shown by the dashed line.

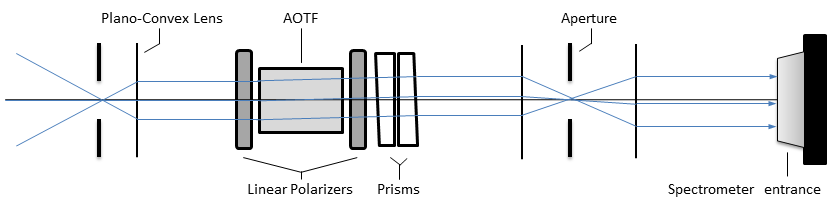


**Figure 3-7**: An AOTF with the RF disabled in the off or “AOTF-off” state. Two linear polarizers are added to the system, the first linear polarizer removes the ordinary polarization represented by the dotted line and the second linear polarizer removes undiffracted extraordinary light shown by the dashed line.

## 3.2.2 AOTF Tuning Curve Analysis

A test optical set up was devised in the lab to determine the output central wavelength relation with regards to the RF, known as the tuning curve, which was determined to know the accuracy and precision of the AOTF to select the central wavelength.

A telecentric test layout was used, which will be described in TODO: 3.2:telecentricSystem. An advantage of the telecentric testing layout is that the wavelength dependence of the acousto effect from the incident angle, noted in equation 3.34, is removed since all the lines of sight enter the AOTF with the same angular spread. The experimental set up consisted of the AOTF being located in the center of two 100 mm focal length lenses to optimally fill the AOTF aperture and linear polarizers were inserted before and after the AOTF to remove unwanted polarizations. An aperture was set up in front and behind the AOTF 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 with sufficient signal but the light entering the spectrometer optics were well collimated and limited the amount of stray light. It also enabled the system to have a much higher degree of telecentricity. Also, 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 3-8.



**Figure 3-8**: 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.

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, which is well below the minimum FWHM of the AOTF specifications listed at 1.6 nm. 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 ATOF 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 spectral are vertical in nature all of the rows of the CCD are summed together to get the total count measurement at each wavelength. The maximum value of each image is taken to be the diffracted wavelength through the AOTF at each respective RF. A typical spectral measurement result can be seen in Figure 3-9a.

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

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

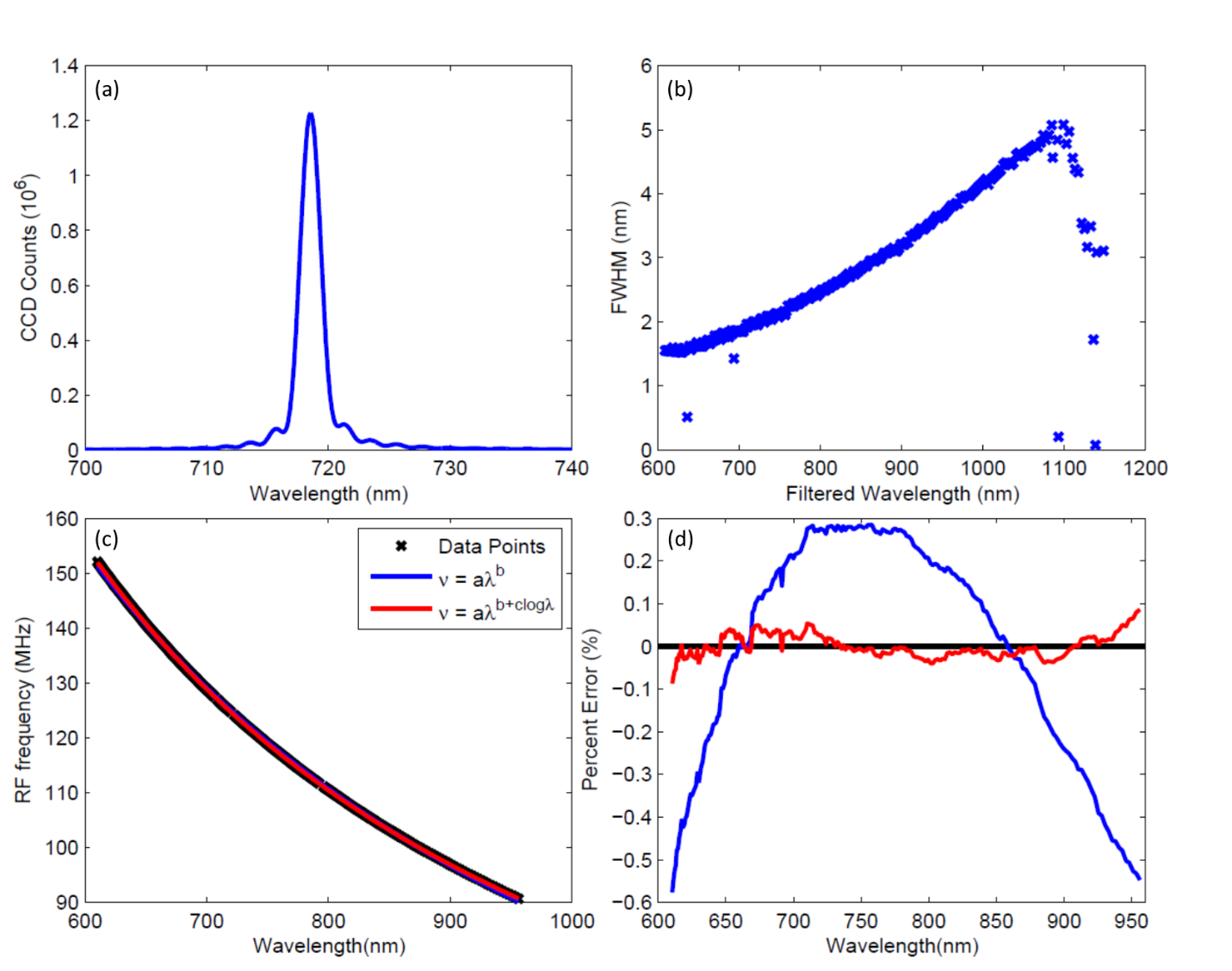
A linear least squares fit was performed in log space finding the coefficients and . The fit was performed and appeared to match the data quite well but a relative error analysis was preformed and it was seen that there was only an agreement better than 0.6% near the edges. A better fit was desired to characterize the AOTF's tuning curve so a modified power function was used in the form of

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

These results of these fits can be seen in Figure 3-9c and Figure 3-9d. The agreement of this form is better than 0.1% throughout the whole wavelength range and the determined tuning curve can be seen in

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

where is in nanometers and is in MHz. 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 3-9**: (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

## 3.2.3 AOTF Point Spread Function

The spectral point spread function of the AOTF were determined. The same set of data that was used to determine the AOTF tuning curve was used to find the spectral PSF by finding the FWHM for each wavelength. These results are shown in Figure 3-9b. The fringes in Figure 3-9a are a known acousto optic effect discussed in section 3.1.2 from the induced RF wave and for the AOTF amount 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.

## 3.2.4 AOTF Diffraction Efficiency

The AOTF’s ability to filter the specified diffracted wavelength is known as the diffraction efficiency. The diffraction efficiency determined using two sets of data; the first set is the data used to characterize the tuning curve of the AOTF, the second set is a measurement of the light that was incident to the AOTF in the wavelength-RF dependence experiment. The second set, or incident set, of data was acquired by removing the AOTF and posterior linear polarizer. The incident light source is measured with the HORIBA spectrometer and Synapse CCD with the same exposure time and settings as the AOTF tuning cure data set. By taking the ratio of the diffracted wavelength counts over the incident counts, the diffraction efficiency was determined. The determined diffraction efficiency is in between 56% to 64% across the measured spectral range and should be noted that the diffraction efficiency changes with respect to incoming angle (*Xu and Stroud*, 1992).

# 3.3 DONE UP TO HERE

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