

The Aerosol Limb Imager: Acousto-Optic Measurements of Limb Scattered Sunlight for 2D Stratospheric Aerosol Profiles

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Abstract

The Atmospheric Limb Imager (ALI) is a prototype atmospheric instrument developed at the University of Saskatchewan with the long term goal satellite instrumentation to gather high resolution horizontal and vertical stratospheric aerosol profiles, including extinction and particle size. The immediate goal of the ALI prototype is to test and verify the use of an Acousto-Optical Tunable Filter (AOTF), the fundamental technology behind ALI, in a space environment and to gather atmospheric sulfate aerosol profiles with high spatial resolution. ALI will measure light from the atmosphere through the limb geometry which measures the radiance from scattered sunlight from sunlit atmosphere. ALI is a single channel instrument measuring radiance from the visible to the near infrared wavelengths (650-950 nm) and through successive images builds spectral information. The system uses a telescopic front end to pass collimated light through the AOTF for each line of sight which is then focused onto the the detector. The AOTF has the property of separating the incoming radiance into each of its linear polarized components and rotating the selected wavelength polarization by 90° allowing one to recover some polarization information of the incoming radiance. The ALI prototype was completed in August of 2014 and a stratospheric balloon test flight from the Canadian Space Agency (CSA) balloon launch facility in Timmins, Ontario onboard the CNES gondola platform occurred on September 20, 2014. Post flight, the method to convert the data into

relative radiances are shown and are used in a MART retrieval method to determine aerosol extinction and size profiles.

1 Introduction

Aerosol has been monitored in several different geometries throughout history. Occultation was one of the first methods used on satellite instrumentation to measure atmospheric species, including ozone. Notable instruments included SAM II (*McCormick et al.*, 1979), SAGE II (*McCormick*, 1987), and SAGE III (*Thomason and Taha*, 2003). Another geometry is the limb scatter geometry which measures radiance from the sunlit atmosphere as it scatters and interacts with molecules. However, the limb scatter geometry has a complexity that requires a forward model to be able to accurately compute the scattering interactions, both single and multiple, between different constituents. Limb scatter was first performed on the Solar Mesosphere Explorer (SME) (*Barth et al.*, 1983) to measure ozone profiles in 1981. Two instruments from the previous generation of remote sensing instruments have successfully used limb scatter to determine aerosol atmospheric parameters, the Optical Spectrograph and InfraRed Imaging System (OSIRIS) a Canadian instrument onboard the Odin satellite (*Llewellyn et al.*, 2004) and SCanning Imaging Absorption spectroMeter for Atmospheric CHartography (SCIAMACHY) onboard the ENVISAT (*Bovensmann et al.*, 1999) which are grating spectrometers that acquire data at a single altitude at a time so a series of exposures is required to create a vertical profile with approximately a 1.5 km and 3 km vertical resolution respectively. The Ozone Mapping Profiler Suite - Limb Profiler (OMPS-LP) *Dittman et al.* (2002) is a current generation instrument which images the atmosphere with spectral and vertical spatial information with 1 km vertical resolution. The new proposed method with ALI allows for two dimensional spatial images of a scanned wavelength with polarized light to be acquired giving both vertical and horizontal resolution of the environment through the use of the innovative AOTF technology.

Sulfuric aerosol is a fundamental portion of the global climate balance. Work by *Andreae et al.* (2005) has shown that global warming has not been as drastic as previously expected due to the high amounts of aerosol in the stratosphere currently due to the high volcanic activity. Aerosol is a spherical particle that scatters incoming radiance

away from the surface of the planet causing an overall cooling effect which is dependant on particle size distribution (*Kiehl and Briegleb, 1993*). This effect is fully defined by aerosol microphysics requiring accurate knowledge of concentration and particle size distributions. Furthermore, high resolution aerosol measurements are required in order to be able to determine aerosol extinction ratios during high aerosol loading due to the long path length and high amounts of scattering. The method of aerosol transportation across the tropopause are not completely understood, recently after the 2011 eruption of Nabro it was determined that the asian monsoon has the ability to penetrate through the thermal boundary and ejected aerosol from the Nabro plume into the stratosphere (*Bourassa et al., 2012*). Current generation instrumentation does not have the necessary resolution needed for current scientific needs and additional horizontal and vertical resolution will allow the determination of aerosol loading from volcanic and anthropogenic sources causing a cooling effect and account for losses from the stratosphere due to transportation that will counteract the previous cooling effect. ALI, a prototype for a next generation of instruments will address the much needed horizontal and vertical resolution improvement required to help answer questions about global climate.

In this paper the first section will outline the technology behind the AOTF used within the ALI system and then describe the optical design behind ALI including an ulterior optical presentation including the comparison with the Belgium instrument ALTIUS. Followed by ALI's maiden flight onboard the CNES CARMEN gondola from the CSA balloon launch facility in Timmins, Ontario including the conditions and trajectory of the flight, and the measurements taken during the campaign including an analysis of the conversion from raw measurements into calibrated data. Lastly, an retrieval algorithm for aerosol extinction and particle size parameters will be outlined and then preformed on the data from the campaign.

2 Instrument Design

2.1 Acousto-Optical Tunable Filter Characteristics

An AOTF uses an acoustic wave, set by a Radio Frequency (RF), that is propagated through the crystal and forms a standing wave to allow the diffraction of a specific wavelength forming a filtering effect. The use of an AOTF for an imaging system has several distinct advantages due to its low mass, fast stabilization times of a few microseconds, and no moving parts and has only recently become possible thanks to improvements to non-collinear acousto-optic devices with the use of birefringent materials with large apertures (*Chang, 1974; Voloshinov et al., 2007*) which allowed for the ability to image with AOTF technology. In order for the AOTF to allow the diffraction of a specific wavelength a momentum matching criteria must be held where the wave vectors of the acoustic wave match the difference of the incoming and diffracted light wave vectors as seen in Figure 1. This condition is known as the Bragg matching criteria and is given by

$$\mathbf{k}_i = \boldsymbol{\kappa} + \mathbf{k}_d \quad (1)$$

where $|\mathbf{k}_i| = \frac{2\pi n_i}{\lambda}$ is the wave vector of the incoming light, $|\mathbf{k}_d| = \frac{2\pi n_d}{\lambda}$ is the momentum of the diffracted light, and $|\boldsymbol{\kappa}| = \frac{2\pi F}{\nu}$ is the momentum of the acoustic wave. The parameters λ , F , and ν are the wavelength in vacuum, the frequency of the RF wave, and the phase velocity in the crystal. The condition given in Equation 1 and the wave vector diagram gives the following relation for a birefringent material undergoing Bragg diffraction

$$\lambda = \frac{\Delta n \nu \sin^2(\theta_i + \alpha)}{F \sin \theta_i} \quad (2)$$

where Δn is the absolute difference between the ordinary and extraordinary indices of refraction, θ_i is the angle of incidence of the incoming light, and α is the cut angle which is the angle from the optical axis to the piezoelectric transducer. Also, through the described interaction the diffracted light goes through a 90° rotation in polarization (*Voloshinov, 1996*). Lastly, a wide aperture is required for an AOTF used for imaging purposes.

In order to be able to perform the required spectral imaging a 10x10 mm aperture imaging quality AOTF was acquired from Brim-

rose of America. It is optically tuned, designed for a specific wavelength octave, for a range of 600 nm to 1200 nm corresponding to a RF range of 156 to 70 MHz and made from Tellurium Dioxide (TeO_2), a birefringent crystal with indices of refraction at 800 nm of 2.226 and 2.373 for the ordinary and extraordinary modes respectively (*Uchida*, 1971). The extraordinary light is diffracted at 2.7 degrees off of the optical axis of the device. In order to achieve a constant diffraction angle of the first order beam a wedge is attached to the exit aperture of the AOTF to compensate for the angular change that occurs from altering the wavelength. The ordinary light undergoes diffraction but at a nonconstant angle off of the optical axis with respect to wavelength due to the ordinary polarization being uncompensated. It is important to note that it is currently not possible to have both polarizations compensated and has such will not be used in ALI.

Characterization of the AOTF is required for use for an instrument. The AOTF is surrounded by a telocentric front and back end to since it will allow the best determination of the central wavelength of the device at a sacrifice of the optimal FWHM results. A 100 mm plano-convex lenses were chosen for both lens to best fill the AOTF aperture. The light source is a 100 W quartz-tungsten halogen bulb that is collimated and passed into the first telocentric lens. The light passes through the AOTF focused then is re-collimated through the second lens. The signal enters a HORIBA iHR320 spectrometer with a maximum spectral resolution of 1.175 nm. The spectral results were imaged on a Synapse 354308 front-illuminated CCD detector with 1024x256 pixels. Images were taken at a set of RFs spaced every 150 kHz from 75 MHz to 160 MHz. For each image the results are spectrally averaged across the rows and a typical spectral measurement result can be seen in the top left panel of Figure 2. The maximum value of each image is taken to be the central wavelength through the AOTF at each respective RF.

The maximum values from each of the images were determined as well as the wavelengths these values occur. It was noted that the curve appears to follow a power function of the form

$$F = a\lambda^b. \quad (3)$$

A linear least squares fit was preformed in log space finding the coefficients a and b . 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 a only an agreement better than 0.6% within the testing

range and would increase for wavelengths outside the testing region. A better fit was desired to characterize the AOTF's RF-spectral dependence so a modified power function was used in the form of

$$F = a\lambda^{b+c \log \lambda} \quad (4)$$

or a quadratic least squares fit. These results can be seen in the bottom half of Figure 2. The agreement of this form is less than 0.1% throughout the whole wavelength range and the determined RF and wavelength relation can be seen in

$$F = \exp(19.793)\lambda^{-3.381+0.168 \log \lambda} \quad (5)$$

where λ is in nanometers and F is in It should be noted that even though the AOTF optical range is 600 nm to 1200 nm this analysis only measures wavelengths from 600 nm to 1080 nm. The low quantum efficiency of the CCD and the low near IR emitted from the light source causes wavelengths past this point to be noisy.

The same set of data was used to determine the FWHM for each of the above determined wavelengths. The results of this study are shown in the top right of Figure 2. Wavelengths past approximately 1080 nm are too noisy to be able to determine the FWHM of the signal which is not a problem since ALI uses a CCD camera which also cannot measure radiances past 1080 nm. However, 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 which is discussed under the section 1.

The diffraction efficiency was determined using the same recorded data from the previous experiment combined with a second set of spectral measurements. The source used in the previous experiment had its radiance passed through the same experiment set up except with the AOTF and the horizontal polarizer removed. These spectral images contained only the initial light that would be incident to AOTF. By directly comparing the counts from the AOTF experiment to the measured incidence radiance the diffraction efficiency of the AOTF is found with a simple ratio. The determined diffraction efficiency is between 56% to 64% across the measured spectral range and should be noted that the diffraction efficiency changes slightly with respect to incoming angle.

2.2 Optical Design and Performance

The AOTF limits the optical system to only have two practical layouts since the incoming light must enter the device at less than the acceptance angle. This is the maximum angle light can enter the device and still undergo the diffraction interaction. These two layouts are a telecentric and a telescopic system. The telescope or afocal system causes a wavelength gradient to be formed across the field of view of the image whereas the telecentric design overcomes this problem but has a larger FWHM (*Suhre et al.*, 2004).

A telecentric layout in both image and object space has an advantage for the imaging quality of the AOTF system. Since the wavelength filtered by the AOTF is dependant on the incident angle to second order Equation 2 and all the lines of sight enter with approximately the same angular spread so the filtered image has consistent central wavelength across the entire image with a larger spectral FWHM since the diffracted wavelength is dependent on incident angle as seen in Equation 2. This system does have two inherent issues. First, this method is sensitive to any surface defects of the crystal since the light enters the crystal in focused bundles.

Second, a blurring effect is added to the final image that is dependant on wavelength. The blurring effect is caused by the inherent change of optical path length. First, the optical path between the first two lenes is a fixed distance, however the AOTF is made of TeO₂ or paratellurite and has a high index of refraction. The crystal also has a high dispersive property, or Abbe number, so the index of refraction depends on the wavelength. The dispersive nature gives an apparent change in the optical path. The change in path length, d , is given by

$$d = \frac{n(\lambda) - 1}{n(\lambda)} t \quad (6)$$

where $n(\lambda)$ is the index of refraction with a wavelength dependance and t is the thickness of the crystal. The AOTF crystal causes the optical path in air to be lengthened by d . In order to compensate, the length d must be added to the path to account to the discrepancy, but this can only be accounted for a specific wavelength due to the high dispersive nature and thus defocusing will occur at the image plane for other wavelengths. In order to correct for this problem additional compensating optics would need to be added or the CCD would need to be actively moved as the wavelengths are being scanned.

In the telescopic system the AOTF has collimated light for each line of sight passing through the device and this has a few fundamental changes that alter the system's imaging quality. First, the light passing through the AOTF from a single line of sight enters the AOTF at the same angle, so the image will have a smaller FWHM than the telecentric counterpart. However, each line of sight will be diffracted with a different fundamental wavelength due to the angular dependance in the AOTF Bragg diffraction wavelength equation (Equation 2). The final image has a smaller spectral bandpass but there will be a wavelength gradient radiating out from the center of the image. Second, since light now passes through the AOTF collimated, the focal point of the image no longer changes with wavelength. Instead a lateral displacement of each line of sight occurs based on the angle of incidence and the diffracted wavelength which causes a slight magnification of the image. The lateral displacement that occurs is given by the following relation

$$\delta = (n(\lambda) - 1) \frac{t\theta}{n(\lambda)} \quad (7)$$

where δ is the displacement from the original path, but this magnification is a negligible change overall amounting to a maximum 0.07 mm exiting the AOTF.

The telescopic system offers the ability of having an image plane location that is not dependant on the wavelength being imaged and was the ultimate optical choice for ALI. A telecentric system would lead to a system that would either require mechanical components to move the imaging plane, additional optical elements to counter act the change in the optical path, or have lower resolution spatially. Using mechanic components to move the camera would be an addition failure point and would have to be well calibrated across the wavelength range. For the second alternative a custom lens or prism would need to be created in order to counteract the defocusing effect of the AOTF which would cause further reflections within the system increasing the possibility of significant stray light and well as decreasing the signal throughput. The telescopic design would also allow for a greater focus on spatial resolution that could be achieved which is necessary in order to be able to image the fine structure of aerosol extinction on the order of 100s of metres.

For ALI a simple three lens optical layout was chosen for the system. Two lens before the AOTF to form the telescopic front end and one lens after to focus the light on for imaging. Consideration was

given when picking the lenses to be able gather a large amount of light and pass it through the AOTF itself in order to reduce the required exposure times during the mission. In order to be able to achieve the increased light throughput a demagnification occurs in the first half of the optical chain resulting in a tightening of the collimated light bundles before entering the AOTF. A slit plate is added At the imaging point between the first two lenses to help reduce unwanted signal from continuing though the optical chain. Before the light enters the AOTF a linear polarizer is used to remove the incoming horizontal polarized light which is the polarization that is not imaged by ALI removing the 0th and 1st order horizontal polarization. After the AOTF the diffracted wavelength has undergone a 90° rotation in polarization so a second linear polarizer orientated vertically is used to remove 0th order vertical polarization. The diffracted light is bent 2.7° from the optical axis and to compensate the rest of the optical chain is bent as well and is passed into an imaging lens which images the signal on a QSI 616s CCD which is a 16 bit output with 1536×1024 $9 \mu\text{m}$ pixels with a 15 count error on the readout. As such ALI measures light that is polarized 90° from the sun or what is known as the vertical polarization. The vertical polarization only account for 10 to 35% of the total incoming radiance. A ray tracing diagram for ALI's optical system was created using the CODE V optical design software and can be seen in Figure 3.

Another minor consideration for the system is the narrower FWHM for each line of sight that passes through the ATOF giving finer spectral resolution however the draw back is that the central wavelength of each line of sight is dependant upon the angle of incident. A wavelength gradient appears in the final image. The longest central wavelength occurs in the center of the image and radiates outward towards shorter wavelengths as apparent in Equation 2. Using the telescopic layout ALI would have a wavelength gradient of approximately 7 nm at 650 nm central wavelength and 11 nm at 950 nm, however for a space based instrument with a relatively smaller field of view the gradient could be reduced to as small as 2 nm across the whole image which, at worse, slightly larger than the FWHM of the AOTF. This effect would be a significant problem for instruments measuring trace gases absorption lines, for example NO_2 , but aerosol is a broadband enhancing feature in which its effects are smooth in atmospheric measurements from 500 nm well into the IR. The wavelength dependent magnification mentioned earlier only amounts to a change of a

approximately 4 pixels or 0.4% in both directions from the inherent magnification from 650 nm to 950 nm and overall this change is considered negligible. The final optical specification for ALI can be found in Table 1.

Instruments that measure the limb have a concern about stray light entering the optical path from paths outside of the systems field of view and contaminating. Even though the AOTF has good method of removing stray light having a large amount of stray light entering the system would drop the signal to ratio and would not be preferable. A baffle was designed and built using the optimal baffle geometry in order to reduce the unwanted signal. The optimal baffle geometry method takes the first stray light ray that would enter the optical chain from the top of the front of the baffle opening to bottom of the back end of the baffle. The intersection point between the stray light ray and the field of view is where the first baffle vein is added. If a stray light ray would pass through this baffle vein it would hit the bottom surface of the baffle before being reflected again. The process was repeated until all required baffle veins are added except now the newest interior baffle is used to determine the minimum stray light ray and the stray light ray reflects once on the interior of the baffle. This design method was done several times with varying lengths and a design was chosen that had reasonably separated baffles. Two extra internal and one extra external 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.

A SolidWorks rendition of the completed version of ALI can be seen in Figure 4. In the prior reference figure, ALI is tilted at 3° from the horizon so ALI's complete 6° field of view would span from a tangent point that would approach the ground to the float altitude.

ALTIUS, a Belgium instrument, uses similar technology as ALI except uses a telecentric optical layout and is designed to measure atmospheric trace gases (*Dekemper et al.*, 2012). Trace gases have narrow absorption and emission features that require specific wavelength knowledge. A telecentric layout will give a constant wavelength across the whole field of view to be able to resolve absorption features. The optical specifications are similar between the two instruments, however two key differences will be noted. First, the field of view of ALTIUS is smaller at $5.73 \times 5.73^\circ$ and if ALI would have used a telecentric design then it would have had an similar field of view due

| | |
|-----------------------------|-----------|
| Effective focal length (mm) | 74.3 |
| Front optics magnification | 0.67 |
| Back optics magnification | 1.27 |
| Field of view (°) | 6.0 x 6.0 |
| F-number | 7.5 |
| Image Size (mm) | 9x9 |
| Image Size (pixels) | 1000x1000 |
| Spectral Range (nm) | 650-950 |

Table 1: ALI Final System Optical Parameters.

to the geometry and optical requirements of the telecentric layout. In a telecentric design the AOTF aperture directly limits your instruments field of view and both systems use an ATOF crystal with an optical aperture of 10x10 mm. Second, the $f/\#$ for ALTIUS is 14.32 compared to ALI's 7.5 which allows ALI to increase light throughput at the cost of slightly higher aberrations in the final image which allowed for a reduction in ALI's exposure time without making a complicated prototype instrument. The visage channel of ALTIUS was breadboarded and testing used to image a smoke stack in order determine NO_2 slant column density at 3.5 km away with a 10 s measurement times. It was noted that improvements to the system would result from methods to reduce the amount the stray light that enters the system as it is non-negligible and a reduction in the time in between measurements.

3 Stratospheric Balloon Flight

3.1 Flight Day Conditions and Flight Path

The balloon launch base in Timmins, Ontario is located at 48.47°N 81.33°W and ALI arrived at the base on August 28, 2014 with a launch window from September 8 to 14, 2014. In between the arrival and launch ALI was integrated onto the CNES CARMEN gondola with CARMEN's systems, including communications and power. ALI was orientated so it would be 90° from the direction of the sun in regard to the gondolas pointing system with an overall southern field of view during the mission. CARMEN is a gondola with pointing capabilities and is piloted from the ground station in Timmins. The point precision

is then fine tuned to a pointing of better than 1° with the use of an onboard star tracker.

The flight of CARMEN was delayed due to poor weather conditions during the launch window. On September 20, 2014 at 05:35 UTC (01:35 local time) ALI was launched as the Nimbus 7 mission onboard the CNES CARMEN gondola from the CSA Timmins balloon launch facility. During the launch, the sky was clear with light winds allowing for an safe and uneventful launch. The ascent of CARMEN occurred in darkness and reached its flight altitude of 36.5 km at 8:17 UTC. First light was observed by ALI at 9:39 UTC and recorded measurements until 14:42 UTC when the primary aerosol mission was completed. ALI was powered off at 17:15 UTC during this time ALI recorded measurement for secondary goals, including an azimuth scan. A visualization of the flight path with all major landmarks noted can be found on Figure 5. Temperature profiles for the ambient atmosphere and instrument can be seen in Figure 6. The black curve is the ambient atmospheric temperature surrounding the gondola during the flight from the ECMWF *Molteni et al.* (1996). The blue, green, and red are from temperature sensors on board ALI for the baffle, camera, and RF driver respectively. The baffle temperature sensor was attached just on the inside of the ALI right by the entrance aperture for the system and monitors the temperature at the front of the system. The camera sensor is attached to the back of the CCD camera and the RF driver sensors measures the temperature of the RF driver. ALI was thermally insulated with styrofoam to keep the system warm, while at the same time direct heating from the sun was a concern for overheating and the system was covered in a reflecting material to reduce solar heating.

During the mission, ALI ran in two primary operational modes, a dark mode and a aerosol imaging mode. The first mode, the dark mode was primarily used during ascent and intermittently between aerosol modes. During this mode the filtering of the AOTF is disabled, meaning with no RF signal being applied to the crystal, and has such the wavelength has no dependence on the images. Eight exposures are taken at with 0.05, 0.1, 0.5, 1, 2, 3, 5, 10 s exposure times and the camera shutter still operated. The second operational mode was for aerosol this mode took 13 measurement sets which consisted of a pairs of images. A pair of images, one with the AOTF enabled and one disabled, were gathered for every 25 nm between 650 to 950 nm each measurement set took approximately 25 s to acquire. The exposure

times were determined by making ground based measurements of all of the wavelengths in the aerosol mode at a variety of exposure times. This data was used to determine the value at which the well of the CCD would be three quarters full on the ground. Then using the known geometry from the ground and assumed geometry from the balloon in combination with the SASKTRAN mode, which will be discussed in subsection 3.3. The determined ground based exposure times were scaled to balloon exposure times by the ratio of the balloon based modeled radiances over the ground based modeled radiances.

3.2 Measurements

ALI's orientation on the CARMEN gondola resulted in a system where ALI only measured 10 to 35% of the total incoming radiance due to the polarization and requires a radiative model that can accurately compute polarization radiances.

The raw flight data (level 0) must be converted to relative radiances (level 1), which are the data scaled to a chosen region of the measurements, before they can be used to retrieve aerosol extinction and particle size. The transformation includes removal of dark current, the DC bias, stray light, and flat fielding. Using the dark images from the ascent of the flight combined with laboratory dark test images a table of values based on exposure time and CCD temperature was computed to be able to remove the DC bias and dark current from each raw image accurately. Once completed, the constant offset caused by the DC bias allows for the rest of the analysis to be preformed in counts per second, simplifying comparisons between images.

Stray light removal has always been difficult in atmospheric instrumentation due to the difficulty in accurately discerning the signal in regards to the stray light contamination. Furthermore, ALI's optical system has the further addition of unwanted light internal to the instrument because of the rejection of one of the polarizations due to the nature of the AOTF. The signal enters the optical system unpolarized, but only one polarization can have a consistent output angle from the AOTF. The entering light is passed through a linear polarizer with an extinction ratio of at least 100,000:1 to remove the unwanted polarization however a small percentage is not absorbed. Furthermore, a second linear polarizer is used after the AOTF to reject all of the unwanted radiance that did not meet the Bragg criteria and once again a small percentage of this radiance is not absorbed. The active filtering

of the AOTF allows for an image to be measured when the filtering device is disabled, which is with no applied RF, allowing only the stray light to be captured by the measurement known as a ‘dark image’, and during ALI’s aerosol mode a ‘dark image’ was captured before every measurement image. By removing the ‘dark images’ from the signal-stray light contaminated images the end result is images that only contain the measured signal. The previous method was tested in the lab with a known source with even illumination across the field of view of the system, the resulting final image is left with a even decrease in intensity radiating from the center of the field of view as its expected with the known vignetting of ALI. The vignetting is caused by the appearance of the AOTF itself, by using a simple optical layout as chosen for the prototype the higher the larger the angle for the field of view the more light that get blocked by the AOTF’s aperture causing a known vignetting for the images and will need to be calibrated out of any measurements.

To finalize the data into level 1 relative radiances a flat fielding calibration is performed which is taking all the incoming fielding of views and normalize them to be unity. The flat fielding coefficients needed to be applied not only spatially across each image but spectrally as well. To determine the flat fielding coefficients ALI was set up in the lab viewing the light emitted from a quartz-tungsten halogen bulb that is passed through a diffusing plate to give an evenly distributed signal across the entire field of view of ALI. Measurements were taken at varying integration times at every wavelengths the same as ALI’s aerosol mode. Since ALI is most sensitive 750 nm it was chosen to be the reference point since it is the wavelength where the system is most sensitive and the center pixel were used since they experience little vignetting, specifically the center 25 by 25 pixels. All pixels for every image were normalized to the reference point pixels. From these normalized images, the flat fielding coefficients were the values needed to multiply the normalized image to achieve unity. The coefficients were then average for each wavelength and used as the flat fielding coefficients and applied to the flight data to yield the final relative radiances.

To increase the precision of the measurements from the flight the images were averaged in cells of 25 horizontal and 10 vertical pixels decreasing the resolution but greatly reduces the noise on the radiances by a factor of 16. Furthermore, a loss of resolution was also noted in the flight data and is caused by the drastic change in temperature

of the optics during the flight which is a secondary reason for the pixel averaging. A large number of vertical profiles with a horizontal dependance are determined. The final relative radiances can be seen in Figure 7.

3.3 Retrievals

The modeled radiances were computed with the SASKTRAN radiative transfer engine (*Bourassa et al., 2008*) for for High Resolution (SASKTRAN-HR) (*Zawada et al., 2015*) measurements using the newly developed polarization module (*Dueck S. and Degenstein*). The model uses a given atmospheric state to solve the radiative transfer equation to determine the final radiance at the observer that follows

$$I(s_1) = I(s_0)e^{-\tau(s_0,s_1)} + \int_{s_0}^{s_1} k(s)J(s)e^{-\tau(s,s_1)}ds \quad (8)$$

where $I(s_1)$ is the radiance at the observer through a path from s_0 to s_1 , the first term is the contribution of light that is attenuated along the line of sight from the sun to the observer at s_1 . The second term takes the source term, $J(s)$, which is the radiance scattered into the line of sight and integrates the path along line of sight with attenuation to determine the scattering contribution to the final radiance. The extinction, given by $k(s)$, is the sum of the number density, $n(s)$, multiplied by the cross section, $\sigma(s)$, over all species. The polarized output of SASKTRAN-HR gives the stokes vectors for the radiance on its internal coordinate grid which can be retrieved from the model and then can be rotated to match ALI's coordinate system.

The relative radiance level 1 data from ALI are used to create a measurement vectors, y , from the data in the following form

$$\mathbf{y} = \frac{I(\mathbf{z}, \lambda)}{I(z_{ref}, \lambda)} - \frac{I_{rayleigh}(\mathbf{z}, \lambda)}{I_{rayleigh}(z_{ref}, \lambda)} \quad (9)$$

where $I(z, \lambda)$ is the measured radiance from ALI and $I(z_{ref}, \lambda)$ is a reference altitude used to normalize the signal from a high altitude where there is little aerosol contribution, for ALI the highest possible altitude where the signal is above the noise threshold is around 26-30 km tangent height which brings out the aerosol signal in the vector. The second term is modeled values from SASKTRAN-HR with only background neutral atmosphere to remove the rayleigh signal from the measured radiances which is done to improve the speed of the

convergence of the retrieval. A base aerosol state or a priori, \mathbf{x} , for aerosol extinction profile is used in the SASKTRAN-HR model. The forward model vector is constructed similarly to the measurement vector and follows.

$$\mathbf{F}(\mathbf{x}) = \frac{I_{mod}(\mathbf{z}, \lambda)}{I_{mod}(z_{ref}, \lambda)} - \frac{I_{rayleigh}(\mathbf{z}, \lambda)}{I_{rayleigh}(z_{ref}, \lambda)} \quad (10)$$

where $I_{mod}(z, \lambda)$ is the modeled radiance for the measurement and $I_{mod}(z_{ref}, \lambda)$ is the measurement at the same reference altitude for normalization. The forward model is used in combination with the measurement vector to update the extinction profile in the Multiplicative Algebraic Reconstruction Technique (MART) algorithm with the following iterative technique

$$x_{i+1} = x_i \sum_j \frac{y_j}{F(z_j)} W_{ij} \quad (11)$$

where i is the aerosol extinction at each measurement altitude and j is the tangent point internal to the SASTRAN model, known as the shell altitudes. W_{ij} is the weighting matrix that relates the tangent altitudes to the shell altitudes. This method was outlined by *Degenstein et al.* (2009) and allows for fast retrievals without calculating a Jacobian.

An error estimation was also needed to be able to fully classify the capabilities of ALI and was performed using a perturbation method. Once a retrieval has been completed for an image the result is used to estimate the error in the returned extinction. For each altitude, the measurement vector is perturbed by the error resulting from the level 0 to level 1 data conversion and from the readout electronics. The MART retrieval is rerun and the change of the extinction is determined. These are compiled to form a Jacobian, \mathbf{K} , with size is n by m which are the shell altitudes and the tangent altitudes grids respectively. The error at each retrieved altitude is then given by

$$\mathbf{e} = \left(\mathbf{K}_{ij} \mathbf{K}_{ji}^{-1} \right)^{0.5} \quad (12)$$

which gives the error at a retrieved altitude.

Once the retrieval has been performed for a complete series of wavelengths a determination for the angstrom exponent occurs which is performed in a similar manner as outlined by *Rault and Loughman*

(2013). Since the measurements observe relatively the same atmosphere over the time of one complete aerosol cycle; the differences between extinction ratios at the different wavelength can be used to gather a understanding of aerosol particle size in the form

$$\frac{n\sigma}{n_0\sigma_0} = \left(\frac{\lambda}{\lambda_0}\right)^{-\alpha} \quad (13)$$

where n is the aerosol concentration, σ is the cross section, and α is the angstrom exponent. Since the cross section of aerosol is dependant on not only the wavelength but also the particle size and distribution the angstrom coefficients give some information on particle size. For the retrieval described here a single mode log-normal distribution is assumed with a mode radius, r_g , and the mode width, σ_g which is commonly used for aerosol profiles (*Bingen et al.*, 2004). At each retrieved altitude the extinction from each wavelength is used to fit a line and determine the angstrom coefficient. Then the median value from all the altitudes is used as the new size parameters in next iteration of the retrieval. The mode width would be set at a constant 1.6 and the mode radius is varied to achieve an identical angstrom exponent as retrieved. The mode radius is updated and the process is repeated until the angstrom exponent converges and at the end of the last iteration the angstrom exponent profile is kept unaltered as the final particle size product.

3.4 Results

In order to be able to use the ALI data in the MART method certain quantities were needed for the model; albedo, ozone concentration and cross sections, and aerosol cross sections. The albedo is required since an absolute radiance calibration was never preformed with ALI and the albedo cannot be determined directly form ALI's measurements, which is important since the amount of ground scatter in SASKTRAN-HR must correspond to the ground scatter during ALI's flight. Second, the ozone absorbtion features from the Chappuis band appear in the ALI measurements from 650 to 750 nm. The absorbtion must be accounted for to not artificially change the determined aerosol profiles. The ozone profiles were acquired from OSIRIS. Five scans that were with 48 hours of the balloon flight and within 500 km of the launch facility were averaged together to be the ozone profile used in the SASKTRAN-HR model, with cross section gathered from the GOME

flight instrument done by *Burrows et al.* (1999). The albedo is from the ADAM database which has monthly values for albedo over the surface on earth at a resolution of $0.1^\circ \times 0.1^\circ$ grid at 1 nm spectral resolution (*Muller et al.*, 2013). The aerosol cross sections come from the Mie scattering derivation that was originally proposed by Mie and was implemented efficiently by *Wiscombe* (1980). It is important to note that the scattering direction and cross section of aerosol particles depends on the size distribution so a knowledge of particle size is required for highly accurate aerosol measurements. For the purpose of the retrieval an a priori was used with a mode radius of $0.08 \mu\text{m}$ and a mode width of 1.6 which is considered a standard size distribution for aerosol (*Deshler et al.*, 2003).

The complete mission consisted of 217 images that were recorded in illuminated conditions and were used in the MART method. The retrieval method was run on the full mission but this paper will focus on a signal set for the purpose of the analysis, specifically the last complete set of images from 650 to 950 nm consisting of images 204-217 will be used. They were chosen due to being the last in the mission and the sun was the highest in the sky giving the brightest atmosphere leading to the best signal to noise during the mission. A sample of the retrieval set can be observed in Figure 8 which highlights the 725, 825, and 925 nm retrievals at 1 km shell resolution. The left panels shows the measurement vector from ALI in black with the forward model radiance profile from SASKTRAN-HR in blue. For each of the wavelengths, the algorithm determines altitudes where the value of the measurement vector is less than the known noise and does not allow aerosol to be retrieved in those regions. Instead the scaling factor, given by $\alpha = yF^{-1}$ is scaled to the aerosol profile above and below the last retrieved point to keep the aerosol profile smooth, as discontinuities are nonphysical and can lead to a convergence failure in the MART algorithm. The middle panel shows the convergence between the measurement vector and the forward model result. For the center wavelengths, being 700-875 nm, a different of less than 2% is seen from 12 to 22 km with a few outliers and for the fringe wavelengths this is reduced to better than 3% from 17 to 20 km.

The aerosol profile for the three wavelengths is shown in blue with the shading representing the error for the retrieval strictly based on measurement error and neglecting any model and atmospheric state errors. The green curve is the average 750 nm aerosol extinction profiles of the same five OSIRIS scans used for the ozone profile and red is

the 750 nm aerosol extinction from SALOMON (*Berthet et al.*, 2002) which was launched from the Timmins balloon base as the Nimbus 5 mission on September 12, 2014. The aerosol extinction for ALI and OSIRIS are within 50% of each other for a majority of the 725 nm and 825 nm profile while the upper altitude of the 925 nm are considerable different, in some places over 100% difference occurs. SALOMON's extinction profile are considerable larger than ALI's results but it is important to note is that all three instruments follow the same shape for all the profiles. First, a bend in the profile occurs at approximately 25 km, then increases approximately linearly until 15 km where aerosol extinction leaves the linear trend and forms the peak of the measurement. The agreement in shape is an excellent result for the ALI mission due to the good numerical comparison with OSIRIS as well as the overall profile shape agreement between all three instruments.

The particle size method was used as outlined in the pervious section using the angstrom exponent to gather a general idea of the particle size distribution during the ALI mission. The first panel of Figure 9 shows the median angstrom exponent that was determined after each iteration and convergence can be seen after a couple iterations. The particle size determined for ALI in the last complete set of aerosol images can be seen in the second panel of Figure 9 which yields a final angstrom exponent of between 2 at the high altitudes (20 km) and closer to 4 near the peak of the aerosol extinction layer around 12 to 15 km. Assuming a mode width of 1.6 yields a mode radius of 0.12 μm and 0.01 μm respectively.

In order to determine the angstrom coefficient a least squares fit was used for all usable wavelengths at each altitude. A wavelength at a altitude was rejected if the forward model at that shell altitude was not within 3% of the measurement vector. In the case shown in Figure 9, the 20.5 km shell altitude, only 8 of the 13 possible wavelength contributed to the angstrom exponent.

4 Conclusions and Future Prospects

A description of the prototype ALI using an AOTF for active filtering in the visible to near IR with a telescopic optical layout with the purpose to measure aerosol extinction from the upper troposphere and lower stratosphere with a high vertical and horizontal resolution with monochromatic images was presented here. The AOTF has fast

stabilization times and the ability to disable the filter gives an excellent method to remove stray light from the final measurements. ALI is able to measure aerosol microphysics in remote atmospheric sensing.

ALI was tested on board the CARMEN gondola from the balloon launch facility at Timmins, Ontario. Aerosol extinction profiles were determined and had good comparisons to ORISIS and SALOMON in profile shape. The absolute extinction values are different by a large amounts but could be attributed to the large amount of unaccounted systematics in the retrieval algorithm. Overall ALI preformed admirably and verified the use of this technology for future atmospheric remote sensing missions.

Future upgrades to ALI would include the realignment of the optics for flight temperatures to allow for higher resolution measurements and retrievals. Secondly, replacing the CCD currently used on ALI with a camera with a faster readout would allow for a higher quantity of data to be taken by reducing the approximate 25 s readout time down to a smaller time necessary for a satellite missions on the order of 1 s per wavelength.

This work would have not been possible without funding from the CSA to design and build ALI through the FAST program as well as the CSA building and managing the launch facility in Timmins, Ontario. Also, thanks to CNES for funding and overseeing the launches at Timmins in 2014. As well thanks Nick Lloyd for help in development of the flight code, without their efforts this work would have not been accomplished.

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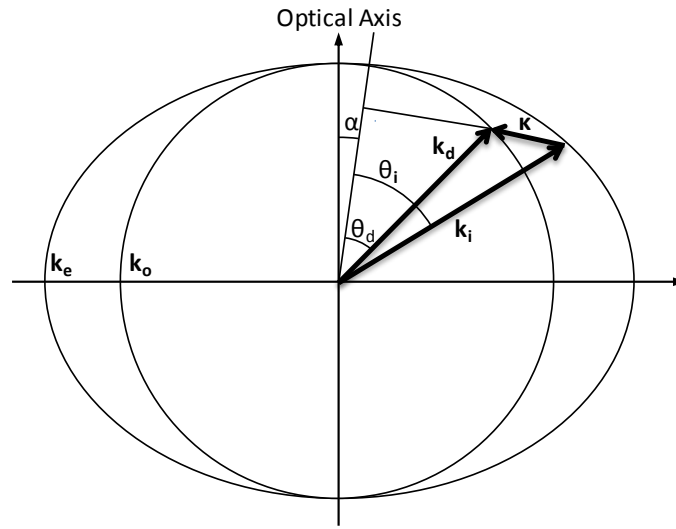


Figure 1: The wave vectors generated by the AOTF experiment. The wave vectors k_e and k_o are for the extraordinary and ordinary axes of the AOTF crystal. The cut angle is shown as α .

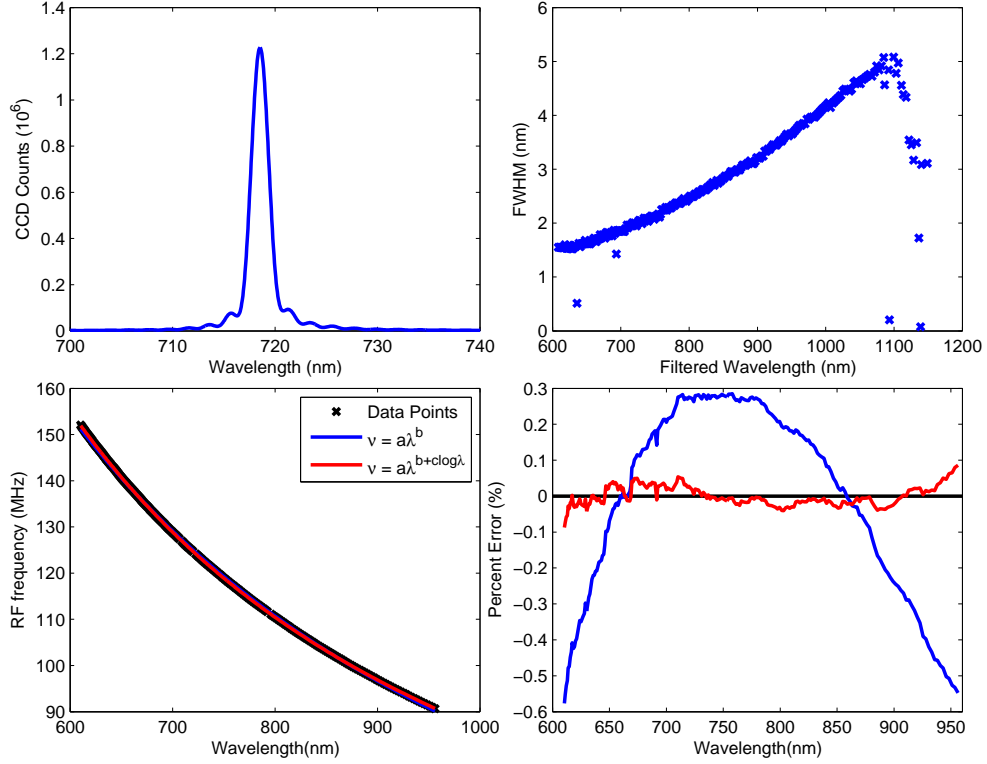


Figure 2: Top Left: A standard image taken from the AOTF calibration experiment when the tuning frequency of the AOTF was at 124.96 MHz. Top Right: The FWHM for each of the determined wavelengths for the AOTF. It should be noted that the FWHM at 600 nm is 1.5 and as the wavelengths get longer the FWHM increases to 4.9 at 1080 nm. Bottom Left: The calibration curves for the AOTF RF versus the diffracted wavelength which contains the data points recorded and two best fit curves. Bottom Right: The percent error with respect to the measured frequency for the two best fit curves in the previous panel.

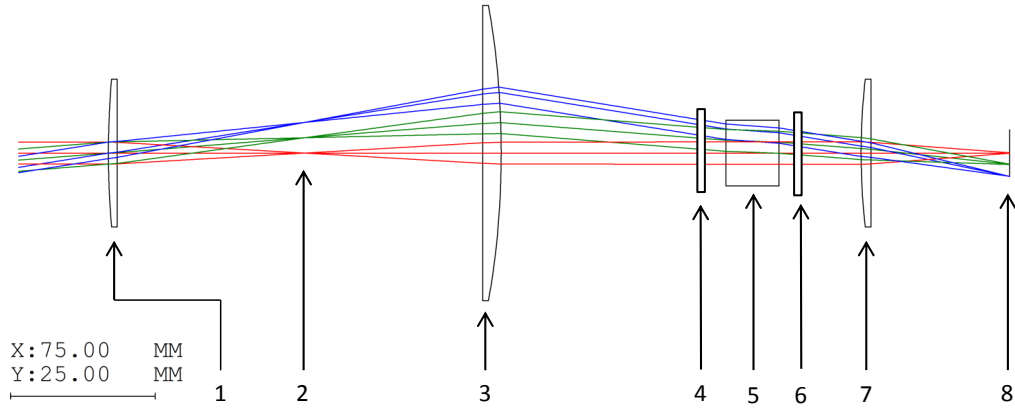


Figure 3: Ray Tracing diagram of the telescopic lens system for ALI simulated by Code V optical design software. The elements in the system are the following: (1) 150 mm focal length plano-convex lens. (2) Slit plate. (3) 100 mm focal length plano-convex lens. (4) Vertical linear polarizer. (5) Brimrose AOTF. (6) Horizontal linear polarizer. (7) 50.4 mm focal length plano-convex lens. (8) Imaging plane. It should be noted that the x and y scales are not the same in this image.

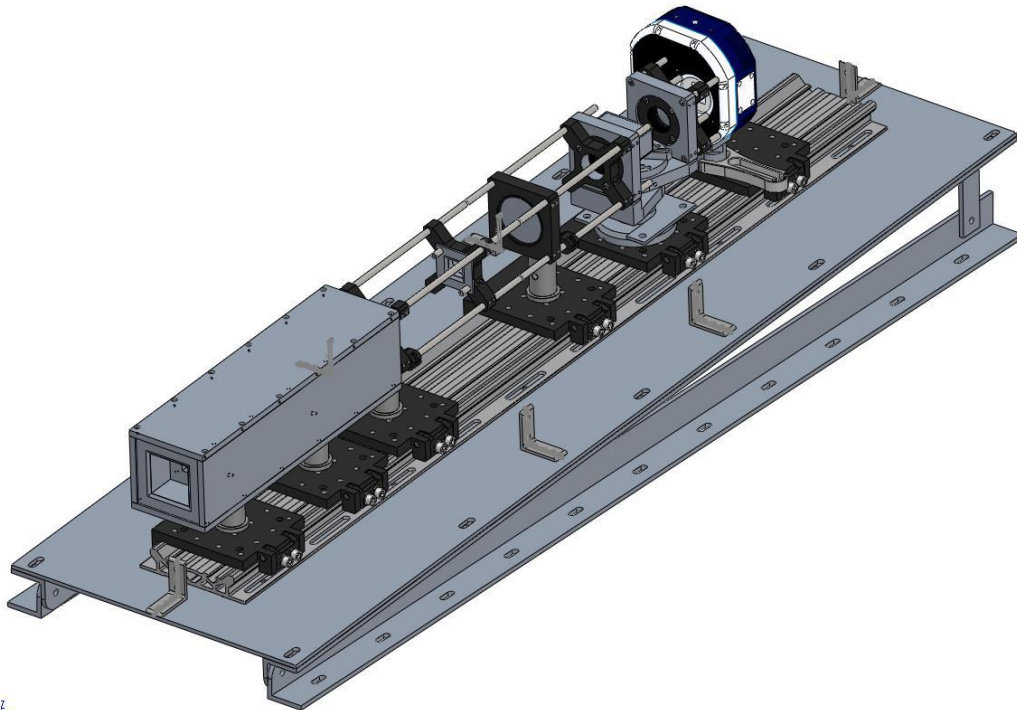


Figure 4: An isometric view of the complete ALI system with the baffle and field of view slant. Light tight case absent from diagram.



Figure 5: The GPS data from ALI during the Nimbus 7 mission generated via Google Earth. The colour of the line represents the absolute speed of the gondola during the mission. Important landmarks are noted on the image. The end of mission represent the end of the primary aerosol mission. No GPS data was collected from ALI after the power down.

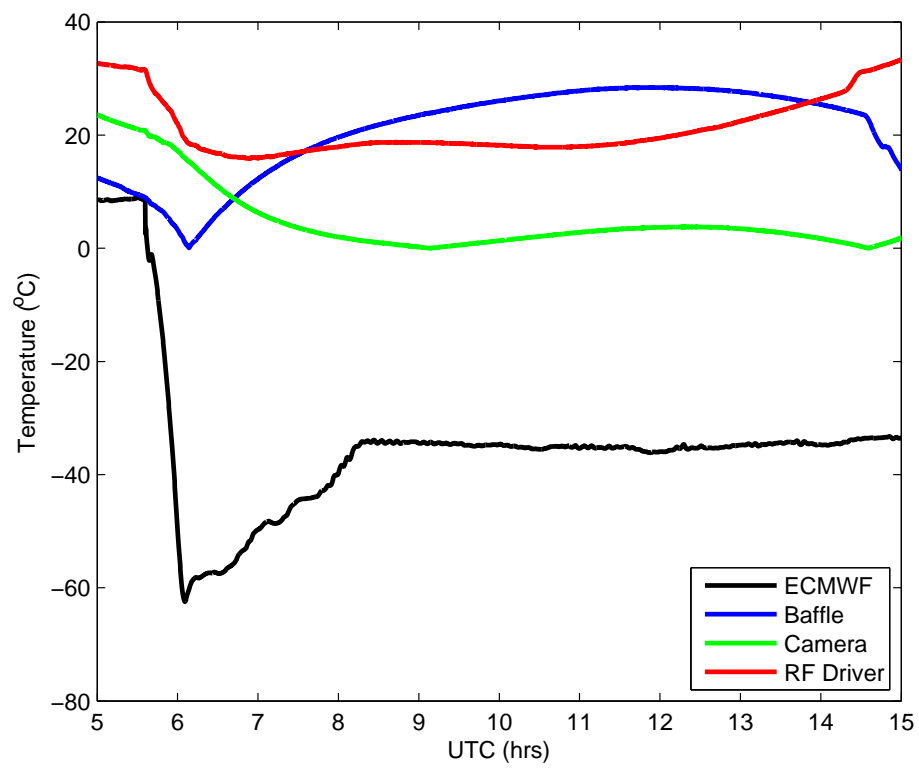


Figure 6: Temperature profiles from the NIMBUS 7 flight.

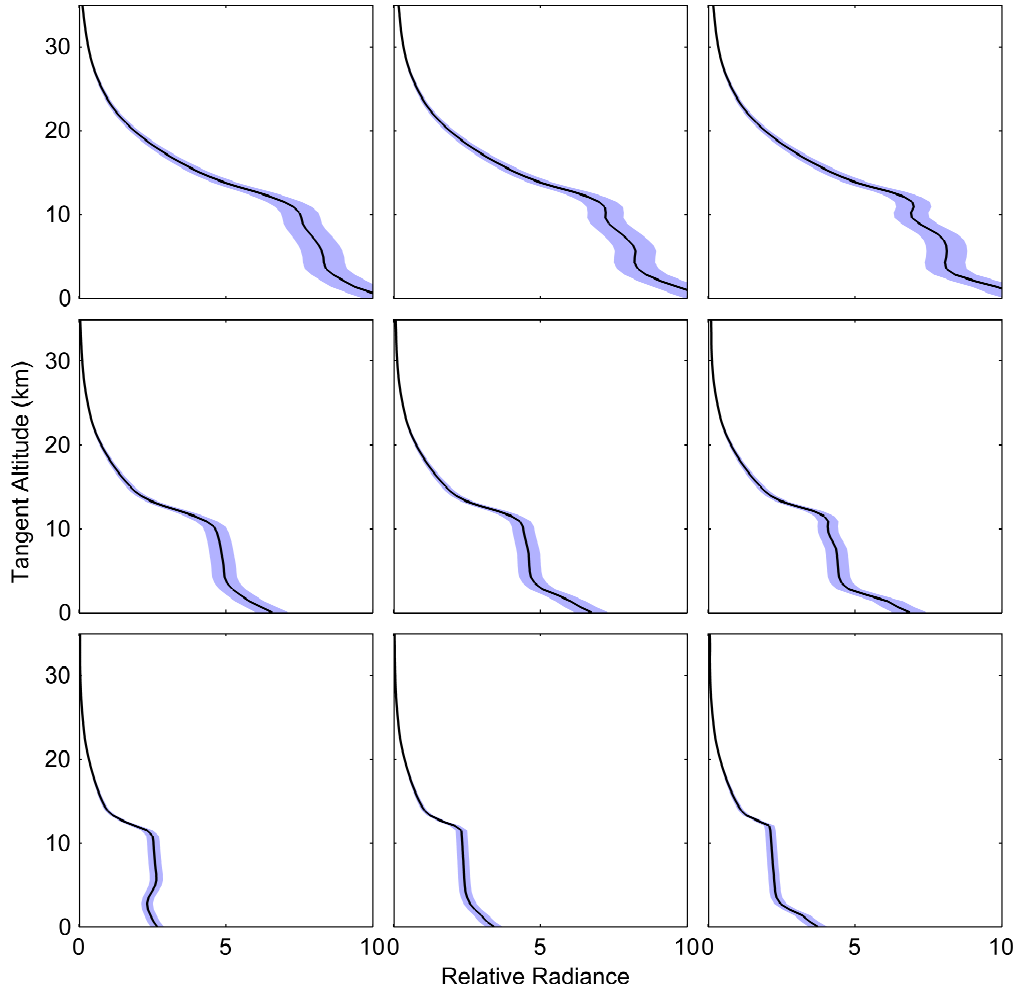


Figure 7: Level 1 relative radiances as measured from ALI at approximately 14:20 UTC (images number 207, 211, and 215) looking 90° from the sun facing southwards. The top middle, and bottom row are measurements taken at 725, 825, and 925 nm respectively. The center column is viewing the atmosphere directly in front of ALI, While the left column is looking to the left at -2.5° and the right at 2.5° .

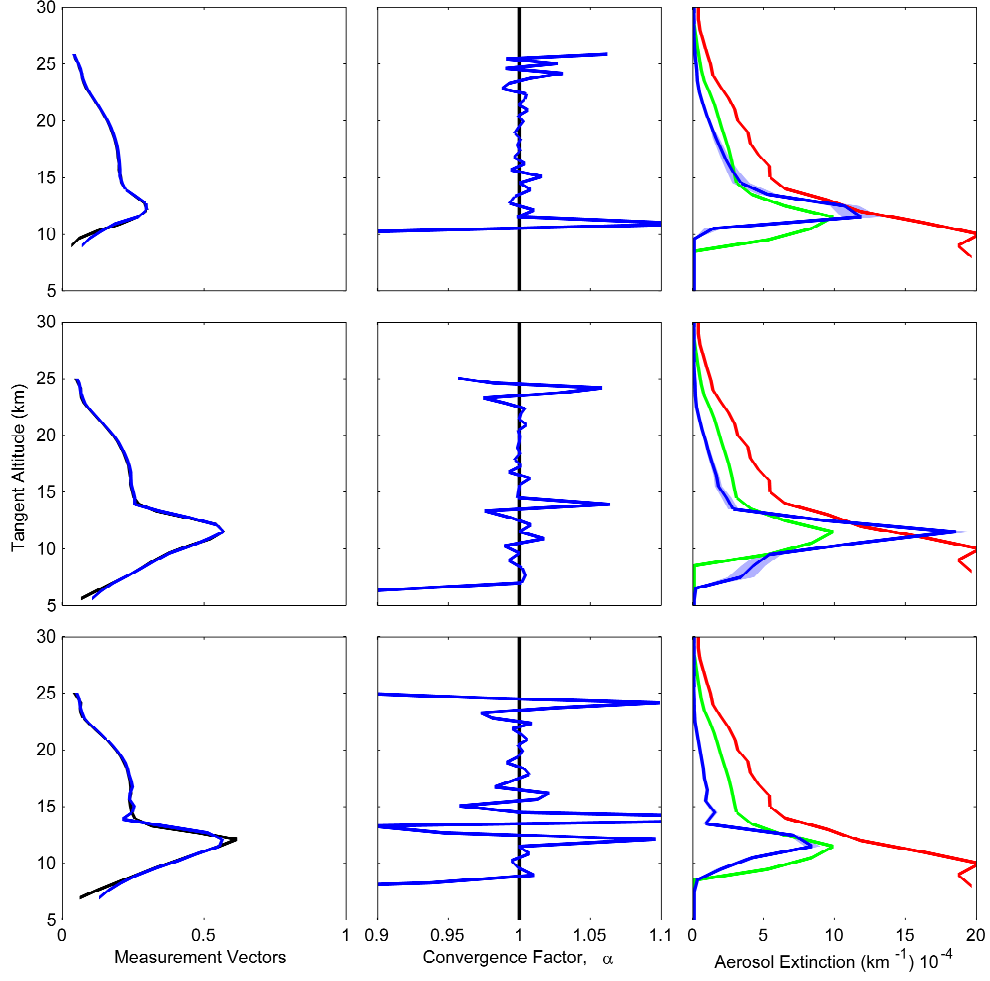


Figure 8: An example of three aerosol retrievals from images 207, 211, and 215, with center wavelengths of 725, 825, and 925 nm respectively and vertically displayed in the figure from top to bottom. The left column shows the measurement vector, y , in black with the retrieved forward model, F , in blue. The center column shows the ratio of the y over F known as α and is the convergence factor between the ALI measurement and the forward model. The final column is ALI aerosol extinction in blue with the associated error represented by the light blue shading. The green is aerosol extinction at 750 nm measured by OSIRIS, and red is 750 nm extinction as measures by SALOMON.

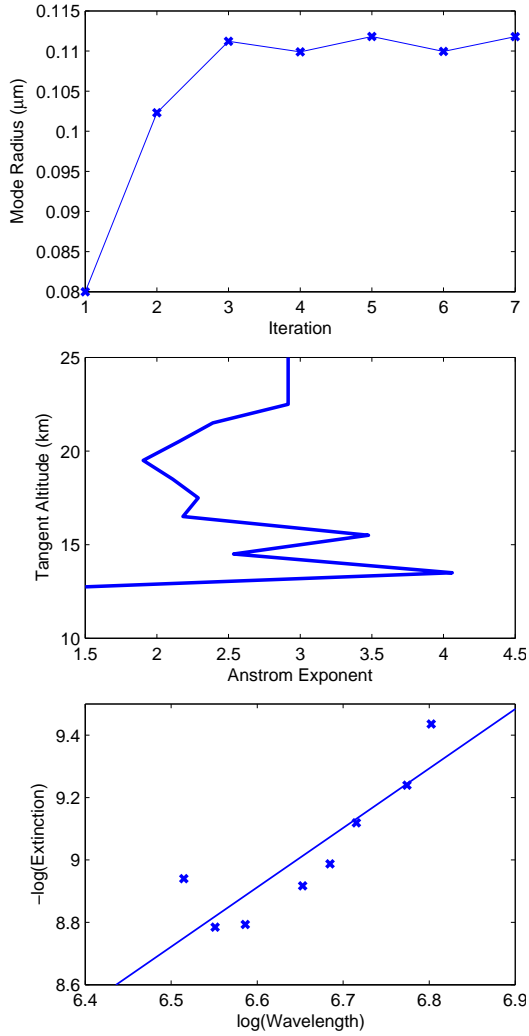


Figure 9: The top panel shows the convergence of the mode radius throughout the iterations in the retrieval. The second panel is the final angstrom exponents determined for images 204-217 during the Timmins 2014 campaign. And the last panel demonstrate a least squares fit to determine the angstrom exponent at 20.5 km shell altitude.