CHAPTER 5

STRATOSPHERIC BALLOON FLIGHT AND AEROSOL RETRIVALS

# 5.1 Stratospheric Balloon Flight

After the completion of the ALI system tests on August 18, 2014 the instrument was transported to Timmins, Ontario and preparation were underwent for the balloon launch from August 25, 2014 until September 19, 2014. During this balloon campaign there were seven balloon launches with ALI being a part of the seventh balloon. The flight of ALI took place on September 20, 2014.

## 5.1.1 Preflight Preparations

The Canadian Space Agency (CSA) balloon launch facility in Timmins, Ontario located at the Victor M. Power Airport (48.47oN 81.33oW). ALI arrived at the base on August 25, 2014 with a launch window from September 8 to 14, 2014. In between the arrival of ALI and the balloon launch, ALI had to be verified to have survived transportation, a seal within the CCD needed to be removed, thermal insulation needed to be added, and finally ALI needed to be integrated onto the Centre National d'Etudes Spatiales (CNES) CARMEN-2 gondola.

ALI was unpacked and set up on a test bench at the launch facility. A visual inspection occurred to verify that no obvious damage occurred to the instrument during transportation. Once completed, ALI was connected to its electronics and power boxes and ALI was powered on. A ground station computer was used to connect to ALI and preform a system check, including verification that of automated startup, telemetry connection was established, that the system powered on correctly with no error and that the science operation program functioned. With this test it was verified that no functional problems occurred to the device during transportation, all temperature and voltage sensors, GPS module, and CCD camera were reporting valid diagnostic values.

Once the ALI system was verified to be operational an imaging check was performed to check that no optical components suffered damage or slippage during transportation. An EIA 1956 resolution target was illuminated by a 250 W tungsten halogen light source and was imaged by ALI to verify the optical layout. The recorded images were very similar to the one taken in the laboratory before the leaving Saskatoon.

Following the successful test of ALI the final preparations were needed prior to beginning integration with CARMEN-2 were performed. First, the CCD used by ALI had a sealed chamber that was in a vacuum state designed to be at atmospheric pressure and would be required to be unsealed before the flight. The unsealing is done in order to not develop a strong pressure gradient between the CCD chamber and the low pressure of a 35 km environment causing permanent catastrophic damage to the CCD detector. At the launch facility ALI was taken to a semi-clean area to unseal the CCD chamber. A panel was removed on the side of the camera and the seal to be removed can be seen in Figure 5-1. The orange o-ring was removed with associated sealing components and the vacuum seal was broken. The chamber panel was replaced and ALI was moved back to the integration hall and another set of test resolution targets were taken to verify the correct operation of the ALI. All resolution target were similar with from the set before the chamber was unsealed expect there was approximately a 5% drop in counts which may have been caused by unsealing the chamber or a change in the lighting conditions of the resolution target.



**Figure 5-1:** Side of the QSI CCD with the panel that contains the vacuum seal opened. The orange o-ring seen in the cavity is removed from the chamber to open the vacuum seal to the camera's CCD chip.

The next step before ALI could be integrated was to add thermal in order to protect ALI from the thermal environment at approximately 35 km. The first thermal concern was the instrument falling to a temperature were the electronics were too cold to function. The instrument would have to be in complete darkness during the assent which would result in little to no solar heating. Furthermore, ALI will pass through the tropopause where temperatures can be as cold as -70oC. Insulation, in the form of foam, was added around the exterior of the instrument to give ALI thermal isolation from the cold environment. The second concern was once CARMEN-2 was at float altitude ALI would have to be able to survive the direct heating from the sun's radiation which could have overheating. The impact of the sun's energy was reduced on ALI by adding a thermal reflector to the outside of the thermal insulation which would reflect a portion of the incoming solar radiation away from ALI.

With the completion of the thermal management, ALI was ready to be mounted onto the CARMEN-2 gondola. ALI can be seen mounted on the CARMEN-2 gondola in Figure 5-2 and ALI used the power and communication subsystems of CARMEN-2. Testing was performed with collaboration from the CARMEN-2 team to check there were no issues between ALI and CARMEN-2’ systems. A problem was found in the communication module, named Siren, between ALI and the ground station computer. With as assistance from the CARMEN-2 team the correct Ethernet setting were determined and a correction to the ALI operation code was applied.

During the integration phase it should be noted that several instruments were also being verified with the CARMEN-2 systems for integration onto the gondola including four other Canadian instruments, including the OSRIS development model (*Kozun*, 2015; *Taylor*, 2015), and SHOW to measure water vapour.

The CNES gondola is an actively pointed gondola with azimuthal pointing precision better than 1’ with the use of an onboard star tracker. ALI was orientated so it would be maintained at 90o from the azimuthal direction of the sun, with an overall southern field of view during the mission.



**Figure 5-2:** The ALI instrument is mounted on board the CARMEN-2 gondola (top shelf on the right). ALI located next to SHOW, another Canadian instrument with collaboration between ABB, York University, and the University of Saskatchewan. ALI has its red tag cover over the optical entrance to protect the instrument from dust and other contaminates. Thermal insulation has been added to the instrument and during the flight sun side will be on the side of SHOW. Some of the reflective layer was blacked out to not cause additional stray light into SHOW optical path.

## 5.1.2 Balloon Flight

The flight plan for the CARMEN-2 gondola was once float altitude was reached and the sun had risen ALI, OSIRIS, and SHOW would perform their operational missions for the first four hours of the campaign. The operation objectives for ALI included a dark imaging suite for calibration purposes, and an aerosol imaging suite for aerosol measurements. A secondary goal was to test the sensitivity to aerosol of ALI with respect to SSA by recording images at various azimuth directions. After the end of the ALI mission, the instrument was to be powered off and other instruments on CARMEN-2 were to gather measurements.

The flight of CARMEN-2 was delayed past it launch window of September 8 to 14, 2014 due to poor weather conditions. On September 19, 2014 at 05:35 UTC (01:35 local time) ALI was launched as part of the Nimbus 7 mission from the CSA Timmins balloon launch facility. During the launch, the sky was clear with light winds allowing for a safe and uneventful launch. The ascent of the gondola 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 spectral images were recorded until 14:42 UTC. ALI was powered off at 17:15 UTC.

A visualization of the flight path with major landmarks noted can be found in Figure 5-3a. Temperature profiles for the ambient atmosphere and instrument are shown in Figure 5-3b. The black curve is the ambient atmospheric temperature at the gondola altitude and location during the flight as obtained from ECMWF reanalysis (*Dee et al.*, 2011). The blue, green, and red are from temperature sensors onboard ALI located on 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 surface temperature of the RF driver. ALI was thermally insulated to keep the system warm whereas the baffle temperature sensor is relatively uninsulated from the extreme cold of the tropopause. The effect of the cold tropopause can be seen on the gondola at approximately 6:00 UTC. The cooling effect can even be seen on the interiors CCD and RF driver sensors which are isolated from the exterior temperature. After, the internal temperature drop the system reaches an equilibrium temperature until the sun light rises and solar radiation comes into contact on the instrument at approximately 10:00 UTC at which point there is an increases in the systems temperature. The temperature of the system are kept within operating range with the aid of the reflective material during the flight.



**Figure 5-3:** (a) 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 represents the end of the primary aerosol mission. No GPS data was collected from ALI after power down. The location of image 208 is the red label. (b) The temperature and altitude profiles from the Nimbus 7 flight. The time of image 208 is shown by the cyan vertical line and first light measured by ALI is occurs at the magenta vertical line.

During the mission, ALI operated in two primary acquisition modes, a calibration mode and an aerosol imaging mode. The first mode, the calibration mode, was primarily used during ascent when the gondola was in the darkness and intermittently between the aerosol mode during sunlit conditions. During this mode the filtering of the AOTF was not enabled and the system imaged essentially only dark current during the ascent in darkness and stray light during sunlit conditions. Eight exposures are taken in the calibration mode with 0.05, 0.1, 0.5, 1, 2, 3, 5, 10 second exposure times.

The second operational mode, the aerosol mode, recorded measurements in a cycle that contained 13 pairs of images across the spectral range (650-950 nm every 25 nm), the pairs being a calibration image with the “AOTF-off” and an image of the limb. Each cycle took approximately 10 minutes with each measurement set taking approximately 40 seconds to acquire with initial exposure times shown in Figure 5-4 in blue which were the exposure times determined during the roof testing of ALI (see section 3.6.1). However, during the flight it was determined that the calculated exposure times were not long enough and the images were underexposed. The underexposure is believe to be caused by the initial exposure time calibration curves being calculated with simulated scaler radiance since the SASKTRAN-HR polarization module had not yet been completed development. So the exposure time curve was recalibrated during the flight using the image statics that were sent down with the house keeping. A comparison of the two exposure time curves with the percent increase can be seen in Figure 5-4. The percent increase is given by

|  |  |
| --- | --- |
|  | (5.1) |

where is the exposure time for the original calibration and are the updated exposure times calculated from the flight.

After a successful flight that lasted for 16 hour 19 minute with the landing at 21:54 UTC. During the flight ALI successfully gathering 216 aerosol images. The gondola landed 70 km from Amos, Quebec or approximately 250 km from the launch facility. CARMEN-2 was recovered by the balloon recovery team and was returned to base on September 21, 2015. ALI was removed from the gondola, repacked and transported back to Saskatoon, Saskatchewan were the data could be processed.



**Figure 5-4:** During the flight the calibrated exposure times was updated. The blue curve represents the exposure times from the ground calibration and the red curve is the recalibration during the flight. The black curve is the percent change in between the pre-flight calibrated results and the during flight calibration.

# 5.2 Limb Measurements

PAPER:

After the successful post-flight recovery of ALI, 216 raw images were obtained and calibrated as detailed in Section 3. An example of a calibrated limb image is shown in Figure 9a. This is image number 208 at 750 nm taken at 13:57 UTC with a solar zenith angle and solar scattering angle of 63o and 98o respectively. The horizontal structure across the images is nicely revealed by calculating the mean radiance profile across the image and then removing it from each profile. This is shown in Figure 9b, where thin clouds (2 km vertical extent or less) are clearly seen near and below the tropopause level, with substantial variation in tangent altitude across the horizontal field of view. These clouds were also observed from other instruments on board the gondola during the mission (B. Solheim, private communication). A brief check on the CALIPSO quick-look plots also shows clouds at a maximum height of approximately 13 km from measurements taken at 08:40 UTC at 47.24oN, 95.25oW, the nearest measurement point to the ALI location and time. Although these images only have a 35 km extent in the horizontal direction, there is also some indication of horizontal variation in radiance significantly above the cloud level, possibly due to real atmospheric variability in the aerosol layer. It should also be noted that some high altitude stray light is also visible in this mean residual image that was not observed in the laboratory tests. This may be due to contamination from scattering from a baffle vein or a nearby component of the gondola, although the true cause is unknown at this point.

For ease of further analysis, and to increase the precision of the measurements to a minimum of 0.6 MTF the images were averaged into cells of 25 pixels horizontally, and average vertically onto a 1 km tangent altitude grid. The radiance profiles from the center column of the images for all measurements obtained during the flight are shown in Figure 10. The first sets of profiles, the dashed lines, which start near zero and move toward larger values, are the measurements that were recorded near and during sunrise so the gradual increase is therefore expected. Measurements obtained for solar zenith angles less than 90o are represented by the solid lines. These radiance profiles follow a similar, and expected exponential shape, with some variability at tangent altitudes below 12 km corresponding largely to changing cloud conditions.

A full cycle of 13 spectral images (numbers 204-216) were used in Figure 11 to show the spectrum of relative calibrated radiances at selected tangent altitudes. The estimated uncertainty in the radiance is represented by the shading. The uncertainty is approximately five percent from 5 to 20 km and increases up to eight percent from 20 to 35 km. The error term includes the CCD read, DC offset, dark current, stray light removal, and flat fielding correction error terms. The spectra display the expected and relatively smooth fall off in intensity with increasing wavelength with Chappuis ozone absorption seen at the lower wavelengths; however, the reason for the peak in the spectra at 875 nm is not known and may be due to an inconsistency in the pre-flight calibration.

THESIS:

ALI arrived back in Saskatoon on September 25, of 2015 and was unpacked and checked for any damages from either the transportation back to Saskatoon or from the landing at the end of the mission. No obvious damage had occurred to ALI and the instrument was functioning correctly. This allowed the complete data set record by ALI to be downloaded and used for aerosol profile processing. This section will undergo the method used to convert the raw data from the CCD to measured relative radiances used in the retrieval process.

The raw flight data, known as the level 0 data, must be converted to into level 1 relative radiances, which is the data normalized to a laboratory measurement value, before they can be used to retrieve aerosol extinction and particle size. The transformation includes removal of dark current, DC bias, stray light, and application of flat fielding calibration.

The DC offset is an bias that is applied to the analogue digital converter inside the CCD camera that causes a bias in the final count values for the image. This need to be removed in order to be able to get the pure measurement counts from the instrument. It is usually assumed that the DC offset for a CCD is a constant across the operating temperatures and exposure times of the device, however the DC offset for the camera used in ALI exhibited a temperature dependance. By using the dark images from the assent of the flight which was in darkness combined with laboratory dark images all of which were takeing at the shortest possible exposure time of the camera, 0.01~s, to remove contribution from dark current. For all the images in the data set the mean value of the counts was used for each image across the whole image. For each each the standard deviation of the counts ended up being 2 to 3 percent of the average value. Using this data a curve was fit to determine the DC offset with respect to temperature and the curve is in the form of

\begin{equation}

\text{DC offset} = 0.00659T^{3}-0.09202T^{2}-3.5368T+643.5127

\label{eqn:5.2:DcOffsetCurve}

\end{equation}

where $T$ is the CCD temperature as measure from the CCD temperature sensor in degrees Celsius and is plotted in \autoref{fig:5.2:dcOffsetCurve}. The dark current is the thermal energy that builds up in the CCD pixels that grows linearly with exposure time and temperature. For the operating temperatures of ALI combined with the short exposure times used during the mission lead to the system having a very small dark current contribution in the measurement images. The dark current was as small as a single count to at most seven counts for the worst case scenario (longest exposure time and hottest temperature.) Since this correction was small compared to the DC offset and the final measurement counts the dark current was added as a a noise contribution for the images. At this point all the non-exposure time sensitive components had been removed and all the images were converted from counts to counts per second by divided the corrected counts by the exposure time.

%by taking the counts in the image and divided by the exposure time, in order to easily relate the radiance of different images directly to each other without having to scale the results with respect to the exposure time.

\begin{figure}

\includegraphics[width=1.0\textwidth]{./Images/5-2-DcOffset.pdf}

\caption[Determined ALI DC Offset]{The determined DC offset determined for ALI in the form seen in \autoref{eqn:5.2:DcOffsetCurve}. The counts on the vertical axis os the counted that need to be removed to remove the DC offset.}

\label{fig:5.2:dcOffsetCurve}

\end{figure}

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. Since only a very small wavelength bandpass composses the wanted signal even small component of the unwanted signal passing through the system adds a considerable amount of stray light. However, 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 instrument which will be referred to as a `dark image'. 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, a 250~W quartz-tungsten light source was passed through a dispersing screen and into the entrance aperture of ALI filling the entire field of view. Using variety of exposure times ranging from 0.1~s to 60~s and wavelengths from 650 to 950~nm in 25~nm internals the incoming source was imaged twice for each unique combination; one image recorded with the AOTF in its off state, with no driving RF wave, and one with the ATOF in its on state, with the RF wave. Once all the images were acquired the DC offset was removed and the counts were divided by the exposure times to give counts per second. Essentially, the image with the AOTF off only contains stray light in the system, as previously stated, and the AOTF on image contains the stray light combined with the even signal from the light source. By subtracting the AOTF off image from the AOTF on image results in an image that just contains the signal and the contamination from the stray light from the system have been removed. Using the images from the experiment the bright areas over the smooth background of the AOTF on images could be successfully removed by subtracting the AOTF off image leaving a resulting image that contains a bright centre with the a smooth fallout in brightness, which is due to the known vignetting of the system. In order to be able to uses this method during the campaign all images captured in the standard aerosol mode will have a corresponding AOTF off or `dark image' recorded as well. An example from the mission with the stray light removal method being preformed is located in \autoref{fig:5.2:strayLightComparison} where the features cause by the stray light are sen to be removed in the final image.

\begin{figure}

\includegraphics[width=0.5\textwidth]{./Images/5-2-StrayLightComparison.pdf}

\caption[Example Stray Light Removal]{An demonstration of the stray light removal method will be preformed using image 208 from the Timmins campaign, which is a 750~nm measurement. The top panel is the image after the DC offset has been removed from a measurement image and in the top right the gradient in the blue raises much higher than in the left portion of the measurement. The middle panel is the associated `dark image' with the AOTF off and the same feature can be seen in the upper right of the image as well as light being registered in the entire right hand portion of the image which should be dark, this is the stray light that is coming into contact with the CCD. The final panel is the the middle panel minus the top panel and the abnormal gradient has been removed from the final image, leaving a clean radiance profile.}

\label{fig:5.2:strayLightComparison}

\end{figure}

The vignetting is caused by the aperture of the AOTF itself, by using a simple optical layout as chosen for the prototype 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. Furthermore the extreme range of the field of view, approximately the last one degree in each direction, is outside the acceptance angle of the AOTF which causes a loss of diffraction efficiency. Both of these effect will also need to be calibrated out of the measurements to achieve final level 1 radiances. To finalize the data into level 1 relative radiances a flat fielding calibration is preformed which is done in two steps: first the images are flat fielded spatially for each wavelength, and second the images are flat fielded over the wavelength range to remove different efficient for different wavelength in the ALI system. In order to determine the coefficients, the final images from the stray light lab test will be used. To determine the spacial flat fielding coefficients the images were sorted into each specific wavelength. Flat fielding coefficients was determined for each pixel in a wavelength set but before starting the analysis, since the images were recorded at various exposures times some images had low signal and some had high signal as such any pixels that were below the noise threshold for the DC offset and completely filled the CCD well were removed for the analysis. Using the rest of the images a coefficient was determined for each pixel of each image to normalize the value of counts per second for every pixel in the form

\begin{equation}

f\_{\lambda, i, j, k} = \frac{c\_{ave, k}}{c\_{\lambda, i,j , k}}

\end{equation}

where $f\_{\lambda, i, j, k}$ is the flat fielding coefficient for a specific pixel location , $i,j$, for for a specific trial image in the wavelength, $k$, $c\_{ave, k}$ is the average of the center 25 by 25 pixels of the trial image, and $c\_{\lambda, i,j , k}$ is the counts per second of the pixel. Over all images in the average pixel value was always with 3\% of the median value for all images. For each wavelength the value of the average flat fielding coefficients, $f\_{\lambda, i, j}$ that was used as the final value and a 3\% error was added to the final counts per second to each pixel. An example of the flat fielding coefficients for the 750~nm wavelength can be seen in \autoref{fig:5.2:flatFieldCoeff}. To achieve the flat field images for each wavelength the following was preformed on the mission data

\begin{equation}

\mathbf{I}\_{\lambda} = \mathbf{C}\*\mathbf{F}\_{\lambda}

\end{equation}

where $\mathbf{C}$ is the stray light corrected image form the mission, $\mathbf{F}\_{\lambda}$ is the matrix of flat fielding coefficients, and $\mathbf{I}\_{\lambda}$ is the flat fielded values.

\begin{figure}

\includegraphics[width=1.0\textwidth]{./Images/5-2-FlatFieldCoeff.pdf}

\caption[750~nm Flat Feilding Coefficients]{The flat fielding coefficients, $\mathbf{F}\_{\lambda}$ for 750~nm. Due to the vignetting the the values near the edge require the largest flat fielding value but a majority of the image has a scaling factor of approximately unity. }

\label{fig:5.2:flatFieldCoeff}

\end{figure}

Once the normalization numbers across the spacial direction had been preformed, a similar methods was done for the spectrally as well. For this method, the average of the 25 by 25 pixel area used for the spacial flat fielding were used again to determine the spectral calibration curve from the specially calibrated data. This curve is simple and the coefficients are given by

\begin{equation}

g(\lambda) = \frac{I\_{ave}(\lambda\_{ref})}{I\_{ave}(\lambda)}

\end{equation}

where $g(\lambda)$ is the scaling factor for the spectral range of ALI, $I\_{ave}(\lambda\_{ref})$ is the average over the center 25 by 25 pixels of the reference the wavelength, and $I\_{ave}(\lambda)$ average the of 25 by 25 pixels at a specific wavelength $\lambda$. The percent errors of the determined $g(\lambda)$ and $I\_{ave}(\lambda\_{ref})$ are 2\% and 1\% respectively across the entire wavelength band. The reference wavelength is 775~nm since it is the wavelength that ALI is most sensitive. The calibration coefficient $g{\lambda}$ and the final flat fielding calibration for a mission image is

\begin{equation}

\mathbf{I(\lambda)} = \frac{\mathbf{C}\*\mathbf{F}\_{\lambda}\*g(\lambda)}{I\_{ave}(\lambda\_{ref})}.

\end{equation}

The final radiance $\mathbf{I(\lambda)}$ is called a relative radiance since it normalized to the 775~nm lab radiance value.

A completed calibration from a raw level 0 image to a level 1 relative radiance measurement can be seen in \autoref{fig:5.2:BeforeAfterImages} and the loss of brightness form the edge portion of the images have been removed and the image has a smooth profile horizontally across the entire field of view. However the noise level for individual pixel were large and in order to increase the precision of the measurements from the flight the images were averaged in cells of 25 horizontal pixels and vertical pixel averaging that would result in the measured radiances being on a 1~km vertical grid. Furthermore, a loss of resolution was speculated to occur in the flight data because of the drastic change in temperature of the optics during the flight which is a secondary reason for the pixel averaging. ALI radiance profiles from the complete mission from the 0\si{\degree} line of sight can be seen in \autoref{fig:5.2:AliRadiancesVectors} which includes wavelengths from 675-950~nm and generally have good internal agreement from 13 to 30~km. A spectrum of relative radiances are shown at a series of altitudes using the measurements from images 204 to 216 in \autoref{fig:5.2:AliSpectralRadiances}. Images 207, 211, and 215 were selected to demonstrate subtle radiance differences between different horizontal lines of sights with each profile's respective error and can be seen in \autoref{fig:5.2:AliRadiances}.

\begin{figure}

\includegraphics[width=1.0\textwidth]{./Images/5-2-BeforeAfterImage.pdf}

\caption[Comparison of an Raw and Calibrated ALI Image]{Comparison of the same image, image number 212, at 750~nm. The upper panel is the raw level 0 data and the lower panel is the relative radiance level 1 data.}

\label{fig:5.2:BeforeAfterImages}

\end{figure}

\begin{figure}

\includegraphics[width=1.0\textwidth]{./Images/5-2-AliRadianceVectors.pdf}

\caption[ALI Relative Radiance Vectors]{All ALI relative radiance vectors from the NIMBUS-7 flight from the straight ahead line of sight, the average of the centre 25 columns of pixels, averaged to a 1~km resolution. Each panel presents the radiance vectors from a different wavelength measured which is denoted in the top right corner.}

\label{fig:5.2:AliRadiancesVectors}

\end{figure}

\begin{figure}

\includegraphics[width=1.0\textwidth]{./Images/5-2-AliSpectralRadiances.pdf}

\caption[ALI Spectral Relative Radiance]{Level 1 relative radiances spectrally from 650~nm to 950~nm as measured form ALI at approximately 14:20 UTC consisting of images number 204 to 216 looking 90\si{\degree} from the sun facing southwards. These spectral profiles are presented at several tangent altitudes with a horizontal field of view of 0\si{\degree}.}

\label{fig:5.2:AliSpectralRadiances}

\end{figure}

The final step in determining the relative radiances is to determine the error on the profiles. Each step in the calibration has an associated error that gets added to the final result. The first step is to analysis the error contributed form the camera readout and DC offset and dark current removal, if the raw image from the CCD is $\mathbf{R}$ with elements $R\_{i,j}$ and $\mathbf{C}\_{raw}$ is the image with the DC offset, and dark current removed then the error contribution would be given by

\begin{equation}

\delta\mathbf{C}\_{raw}^2 = \frac{\delta\mathbf{R}}{t} = \frac{\delta\mathbf{e}\_{r}^{2} + \delta\mathbf{e}\_{DC}^{2} + \delta\mathbf{e}\_{dark}^{2}}{t}

\end{equation}

where $\delta \mathbf{e}\_{r}$ is the read error from the camera which is listed to be 15 counts, $\delta \mathbf{e}\_{DC}$ is the error cause by the DC offset which was determined from the calibration via the standard deviation to be approximately 30 counts, $\delta \mathbf{e}\_{dark}$ us the error added from the dark current removal which is 5 counts at worse, and $t$ is the exposure time. The same method is used for the `dark image' and the final result is denoted $\mathbf{C}\_{stray}$. At this point each image has its stray light removed with a `dark image' subtraction yielding an error of

\begin{equation}

\delta\mathbf{C} = \delta\mathbf{C}\_{raw} + \delta\mathbf{C}\_{stray}.

\end{equation}

The final error is added via the flat fielding process yielding the final error on each image

\begin{equation}

\delta\mathbf{I(\lambda)} = \frac{\delta\mathbf{C}\mathbf{F}\_{\lambda}g(\lambda)}{I\_{ave}(\lambda\_{ref})} + \frac{\mathbf{C}\delta\mathbf{F}\_{\lambda}g(\lambda)}{I\_{ave}(\lambda\_{ref})} + \frac{\mathbf{C}\mathbf{F}\_{\lambda}\delta g(\lambda)}{I\_{ave}(\lambda\_{ref})} + \frac{\mathbf{C}\mathbf{F}\_{\lambda}g(\lambda)\delta I\_{ave}(\lambda\_{ref})}{I\_{ave}(\lambda\_{ref})^{2}}.

\end{equation}

This error was rather large for analysis and was reduced by the averaging of pixels together. As mention earlier the image was banned into 25 horizontal bins and a vertical resolution to yield results on a 1~km grid. In order to determine the final error from the relative radiance the error must be combined from the following

\begin{equation}

\delta I\_{final}(\lambda) = \frac{(\Sigma^{n}\_{i}\Sigma^{m}\_{j}\delta I(\lambda)\_{i,j}^{2})^0.5}{nm}

\end{equation}

where $i$ and $j$ is the index of horizontal and vertical pixel locations and and $n$ and $m$ are the number of pixels to be summed horizontally and vertically respectively. The final binned relative radiance profiles with the associated error for three horizontal field of vie can be seen in \autoref{fig:5.2:AliRadiances}.

%and used to normalized the full field of view across the whole spectrum to the center of the 750~nm images, thus giving a relative calibration of radiance referenced to this point. The process used to determine the flat fielding coefficients started with similar process used to remove the stray light during the mission post processing. The images had the DC bias and dark current removed for proper unbiased comparisons and converted to counts per second. Each value of every pixel in the active region of the CCD was normalized to the mean of the value on the center 25 by 25 pixels at 750~nm over all exposure times and trials. The coefficients for flat fielding can be determined as the values to yield a unified radiances of one across all field of views and wavelengths. These coefficients are then applied to the data from the flight that give relative radiances for each pixel.

\begin{figure}

\includegraphics[width=1.0\textwidth]{./Images/5-2-AliRadiancesWithError.pdf}

\caption[ALI Relative Radiance Vectors with Error and Horizontal Variance]{Level 1 relative radiances as measured from ALI at approximately 14:20 UTC (images number 207, 211,and 215) looking 90\si{\degree} from the sun facing southwards. The top, middle, and bottom rows are measurements taken at 725, 825, and 925~nm respectively and each row is comprise from a single image with a different horizontal line of sight with the respective calibration and readout error shown by the blue shading. The center column is viewing the atmosphere with a 0\si{\degree} line of sight, while the left column is looking to the left at -1.5\si{\degree} and the right at 1.5\si{\degree}. The difference in the radiance profiles demonstrates ALI sensitivity to horizontal distributions in atmospheric composition, specifically aerosol.}

\label{fig:5.2:AliRadiances}

\end{figure}

# 5.3 Aerosol Retrievals

Test

## 5.3.1 Aerosol Extinction Retrieval Methodology

Test

## 5.3.2 Aerosol Extinction Retrievals

Test

## 5.3.3 Particle Size Retrieval Methodology

Test

## 5.3.4 A Sample Particle Size Retrival

Test

# 5.4 Results

Test