CHAPTER 5

STRATOSPHERIC BALLOON FLIGHT AND AEROSOL RETRIVALS[[1]](#footnote-1)

# 5.1 Stratospheric Balloon Flight

After the completion of the calibrations and the system tests on August 18, 2014, ALI was transported to the Canadian Space Agency launch facility in Timmins, Ontario, to prepare for the balloon test flight. Integration and system testing on the gondola occurred from August 25, 2014 until September 18, 2014. During the campaign, there were seven balloon launches, including the ALI flight on the seventh balloon on September 19, 2014.

This chapter explains the procedures used to integrate the instrument onto the gondola for the stratospheric balloon flight. Following, results from the flight are presented including flight path, instrument parameters, and sample calibrated relative radiance images. Finally, scientific results from the flight measurements are presented, including retrieved multi-spectral aerosol extinction profiles, and particle size information.

## 5.1.1 Preflight Preparations

The Canadian Space Agency (CSA) balloon launch facility in Timmins, Ontario is located at the Victor M. Power Airport (48.47◦N 81.33◦W). The ALI shipment arrived at the base on August 25, 2014 with a scheduled launch window from September 8 to 14, 2014. Before the launch, several tasks were performed including verification of system performance after shipping, removal of a seal on the detector array to allow for low pressure operation, thermal insulation of the case, and integration onto the Centre National d'Etudes Spatiales (CNES) CARMEN-2 gondola.

The system check included verification of automated startup, establishment of telemetry connection, ensuring that the system powered on all components with no errors, and that the science operation program functioned. This test verified that no functional problems occurred to the instrument during transportation, and all temperature and voltage sensors, GPS module, and CCD camera were reporting valid diagnostic values.

An imaging check was performed in the integration hall to verify that no optical components suffered damage or misalignment 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 ones taken in the laboratory before leaving Saskatoon.

An important final item of preparation before integration with CARMEN-2 gondola was removal of the detector seal. The QSI CCD detector was in a vacuum-sealed chamber designed for operation at atmospheric pressure. This seal was removed so as to not develop a pressure gradient between the detector chamber and the low pressure environment of the stratosphere, which could cause permanent catastrophic damage to the detector. Following manufacturer advice, the orange o-ring shown in Figure 5-1 was simply removed and the camera panel replaced. Following this another set of test resolution target images were taken to check for any impact of this operation. Results were very similar to the set of measurements taken before the seal was removed, except for an approximately 5% drop in overall signal level. Although this may have been caused by unsealing the detector it is more likely due to a change in the lighting of the resolution target in the non-optimal conditions of the integration hall. With all optical and electronic verifications complete the thermal insulation discussed in section 3.4.4 were added to ALI.



**Figure 5-1**: The QSI CCD with the panel that covers the vacuum seal removed. The orange o-ring seen in the cavity is removed from the chamber to break the vacuum seal on detector.

The mounting of ALI on the CARMEN-2 gondola is shown in Figure 5-2. ALI used the power and communication subsystems of CARMEN-2. Testing was performed in collaboration with the CARMEN-2 engineering team to verify that there were no issues between ALI and CARMEN-2 systems.

It should be noted that several other instruments were also integrated on the CARMEN-2 gondola alongside ALI including two other Canadian remote sensing instruments: the OSIRIS-DM (Developmental Model) (*Kozun*, 2015; *Taylor*, 2015) and SHOW (Spatial Heterodyne Observations of Water), which measures water vapour and was developed by a collaboration between ABB, York University, and the University of Saskatchewan.



**Figure 5-2**: The ALI instrument is mounted on board the CARMEN-2 gondola (top shelf on the right). ALI located next to SHOW. ALI has a cover over the optical entrance to protect the instrument from dust and other contaminates. Thermal insulation has been added to the instrument exterior. Some of the reflective covering was blacked out to not cause additional stray light into SHOW optical path.

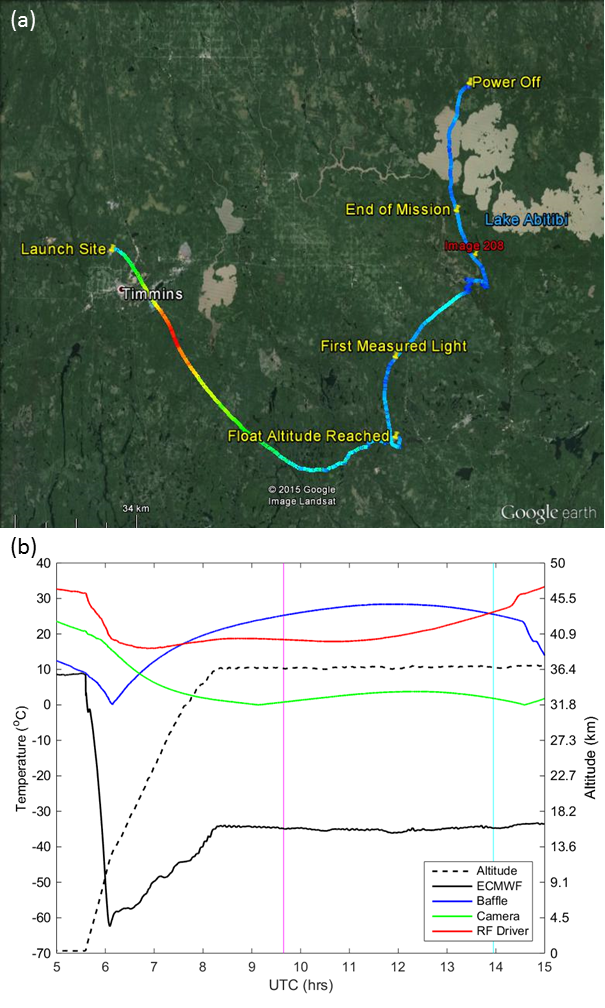
The CNES gondola is an actively pointed gondola with azimuthal pointing precision better than 1’ with the use of an onboard star tracker. ALI was orientated so it would be maintained at 90◦ from the azimuthal direction of the sun, with an overall southern field-of-view during the flight.

## 5.1.2 Balloon Flight

The flight plan for the CARMEN-2 gondola was to launch near sunrise, and provide at least four hours of sustained sunlit measurements at a float altitude of greater than 35 km before descent. The operational objectives for the ALI flight were operationally simple: to collect a suite of dark (AOTF-off) measurements for calibration purposes, and to collect several full spectrum limb images for aerosol retrieval. A secondary, optional, goal was to test the sensitivity of ALI to solar scattering angle by recording images at various azimuthal directions by rotation of the gondola with respect to the sun.

The flight of CARMEN-2 was delayed past its 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. Due to the very early launch window, 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 over an hour later 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 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 sensor 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 environment. 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 interior CCD and RF driver sensors which are thermally isolated from the exterior temperature. After the internal temperature drop, the system reaches an equilibrium temperature until the sun rises and solar radiation comes into contact on the instrument at approximately 10:00 UTC at which point there is a small and gradual increase in the system temperature. All of the temperatures were kept within operating range throughout 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 and the blue, green, red colours represent speeds of approximately 10, 70, and 140 km/h. Important landmarks are noted on the image. The end of mission represents the end of the data collection. 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 occurs at the magenta vertical line. Originally published as Figure 8 in *Elash et al.* (2016).

During the flight, ALI was operated in two primary acquisition modes, a calibration mode and a limb imaging mode. The first mode, the calibration mode, was primarily used during ascent when the gondola was in darkness and intermittently between the limb imaging mode during sunlit conditions. During this mode, the AOTF was kept in the “off” state and the system imaged essentially only dark current during the ascent in darkness and dark current plus stray light during sunlit conditions. Eight exposures were taken in the calibration mode with 0.05, 0.1, 0.5, 1, 2, 3, 5, 10 second exposure times.



**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.

The second operational mode, the limb imaging mode, recorded measurements in a cycle that contained 13 pairs of images across the spectral range (650-950 nm every 25 nm). Each pair of images included 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 45 seconds to acquire with initial exposure times shown in Figure 5‑4 in blue. These were the exposure times determined during the ground based testing of ALI (see section 4.4.1). However, during the flight it was determined that the calculated exposure times were not long enough and the images were somewhat underexposed. The commanding software allowed adjustment of the exposure times during the flight using the image statistics that were sent down with the housekeeping data stream. 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

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|  | (5.1) |

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

The Nimbus 7 flight lasted for 16 hours 19 minutes with a successful landing at 21:54 UTC. During the flight, ALI successfully gathered 216 limb 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 the base on September 21, 2015. ALI was removed from the gondola, repacked and transported back to Saskatoon, Saskatchewan.

# 5.2 Limb Measurements

After the successful post-flight recovery, ALI was unpacked and checked for any damage in Saskatoon, SK on September 25, 2014. No obvious damage had occurred to ALI from the flight and the instrument was tested to verify no internal damage had occurred. There was no damage sustained to ALI from the flight. 216 raw limb image pairs were obtained from the flight and the calibration was performed, including the pointing alignment discussed below and the image calibrations detailed in section 4.4.

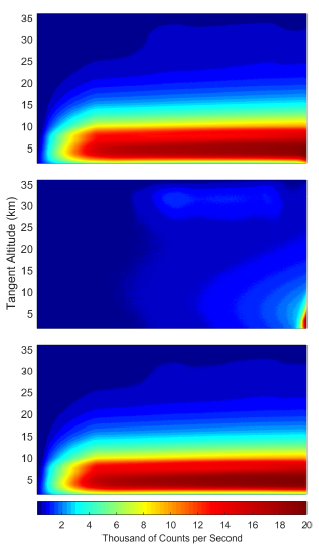
ALI recorded the position and altitude information of each measurement from the onboard GPS but the pointing, i.e. orientation, information was determined by the gondola system. Azimuth and zenith directional information are needed to determine the mapping of the line-of-sight of each pixel on the CCD to the atmospheric limb. The CNES team was able to supply the Solar Azimuth Angle (SAA) information at high time resolution and this was correlated to the images using GPS time. The zenith direction was only specified in terms of stability, *i.e.* time periods when no motion was detectable to within 0.1◦. These stables periods were used in the following analysis. Therefore some manual calibration of the absolute zenith angle was required. ALI was mechanically tilted at 3◦ to allow the full 6◦ field of view to image the limb from the ground to float altitude. Thus the zenith angle of the center of the field-of-view was initially assumed to be 93◦ assuming a balanced gondola. However, there is no guarantee that the gondola was perfectly balanced so a manual calibration was performed by varying the zenith angle from 92◦ to 94◦ in 0.1◦ intervals and the tangent altitude was calculated for each case. Then the radiance profiles for each zenith angle was compared to find zenith angles where the features were aligned, such as cloud radiance features whose tangent altitudes occur below the tropopause. The zenith angle with the optimal alignment was determined to be 92.6◦. An uncertainty of 0.1◦ was determined from this analysis, which agreed with the stability rating of the gondola.

The calibration techniques discussed in section 4.4 were then applied to the raw images to produce the final calibrated radiance. As an example, image number 208 is used to demonstrate the steps in the calibration on a flight image. Image 208 was recorded with a wavelength of 750 nm and taken at 13:57 UTC with a SZA and SSA of 63◦ and 98◦ respectively. The dark current and DC offset have been removed from image 208 using Equation 4.5. Next, the stray light is removed by using the “AOTF-off” or calibration image and removing it from the “AOTF-on” or measurement image. The result of this procedure can be seen in Figure 5-5. In the first panel, abnormal bright spots are noticed in the right side and the top right of the measurement. These same features are noticed in the stray light image. By subtracting the AOTF-off image from the measurement image, a final smooth measurement image is noted in the last panel. Finally, a flat fielding calibration is performed (see section 4.4.5) and a final calibrated image can be seen in Figure 5-6a. Remember that no absolute calibration was performed on ALI, so the radiance is relative to the 775 nm laboratory calibration in arbitrary units. The error, , on a given pixel for the radiance measurements were given by

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|  | (5.2) |

where is the readout uncertainty from the CCD, which is 15 counts at worst, is the error in the DC offset calibration, is the error from the dark current in the CCD, is the error in the stray light calibration, and is the error in the flat field corrections. The average error per pixel was approximately 14-21% of the radiance. Most of the error for the radiance is from the flat fielding calibration accounting for approximately three-quarters of the overall error. The last quarter comes from a combination of the other four sources.

From image 208, the horizontal structure across the image is nicely revealed by calculating the mean radiance profile across the image and then removing it from each profile, *i.e.* each column of pixels. This is shown in Figure 5-6b, 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 FOV. These clouds were also observed from other instruments on board the gondola during the mission (B. Solheim, private communication, 2014). 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 47.24◦N, 95.25◦W, 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. For the high altitudes in the range of 27 to 30 km the expected ratio of signal to stray light was estimated to be between 2-3, but for the campaign the ratio of signal to stray light for some regions dropped down to slightly below one. 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.



**Figure 5-5**: Stray light removal technique was performed using image 208 which is a 750 nm measurement. The top panel is the image after the DC offset has been removed from the measurement. The middle panel is the associated AOTF-off image and stray light features are seen in the upper right of the image as well as light being registered in the entire right side of the image. The final panel is the first panel minus the second panel and the abnormal gradient has been removed from the final image, leaving a cleaner radiance profile.



**Figure 5-6**: (a) Final calibrated 750 nm image, taken at 13:57 UTC located at 48.55◦N, 80.00◦W with a SZA and SSA of 63◦ and 98◦ respectively. The horizontal FOV is 30 km.(b) The same 750 nm image with the mean of the profile removed from the image leaving the residual signal that shows thin clouds in the troposphere. Originally published as Figure 9 in *Elash et al.* (2016).



**Figure 5-7**:Averaged ALI relative radiance vectors from 12 of the 13 wavelengths from the Nimbus 7 flight. Each panel presents the radiance vectors from a different wavelength measured which is denoted in the top right corner. The dashed lines are radiance profiles where the SZA is greater than 90◦ and solid lines are profile where the SZA is less than 90◦. Originally published as Figure 10 in *Elash et al.* (2016).

For ease of further analysis, and to decrease the uncertainty of the measurements to a minimum of 0.6 MTF, the images were averaged into cells of 25 pixels horizontally and averaged vertically onto a 1 km tangent altitude grid. The errors for the averaged radiances, , is given by

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|  | (5.3) |

where the errors for each pixel, , are summed in vertical, , and horizontal, , directions from the starting pixel, for the vertical and for the horizontal, to the final pixel in the average, for the vertical and for the horizontal. For the portions of the image used for aerosol retrievals this ended up being 4-7% of the overall radiance.

The radiance profiles from the center column of the images for all measurements obtained during the flight are shown in Figure 5-7. The first set of profiles, the dashed lines, which start near zero and move toward larger values, are the measurements that were recorded near and during sunrise (*i.e.* SZA greater than 90◦) so the gradual increase is therefore expected. Measurements obtained for SZAs less than 90◦ 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.



**Figure 5-8**: Relative radiances spectrally from 650 nm to 950 nm as measured from ALI at approximately 14:20 UTC consisting of images number 204 to 216 looking 90◦ in the azimuth from the sun facing southwards. These spectral profiles are presented at several tangent altitudes with a horizontal look direction of 0◦. The shading represents the error on the radiances. Originally published as Figure 11 in *Elash et al.* (2016).

A full cycle of 13 spectral images (numbers 204-216) were used in Figure 5-8 to show the spectrum of relative calibrated radiances at selected tangent altitudes. The estimated uncertainty in the radiance is represented by the shading and was calculated using Equations 5.2 and 5.3. The uncertainty is approximately five percent from 5 to 20 km and increases up to eight percent from 20 to 35 km. The spectra displays 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.

# 5.3 Aerosol Retrievals

From the successful flight, radiance measurements from ALI were used to determine aerosol parameters. The following sections describe the Multiplicative Algebraic Reconstruction Technique (MART) retrieval method used to determine aerosol extinction and particle size information. The retrieved aerosol profiles from ALI is presented and is compared to the OSIRIS version 5.07 aerosol extinction product for coincident satellite overpasses. Following, a cycle of aerosol measurements are used to determine a particle size distribution estimate that is compared with particle size parameters from other instruments.

## 5.3.1 Aerosol Extinction Retrieval Methodology

The inversion of the ALI radiances used a Multiplicative Algebraic Reconstruction Technique (MART), discussed in section 2.6.3. Specifically we have applied a slightly modified version of the standard OSIRIS stratospheric aerosol extinction retrieval (*Bourassa et al.*, 2007; 2012b). This inversion algorithm, which is applied from the tropopause to 30 km altitude, assumes log-normal distributed hydrated sulphuric acid droplets (see Equation 2.1) in order to calculate the aerosol scattering cross section from the Mie scattering solution. The modeled radiances for the nonlinear inversion were computed with the SASKTRAN-HR radiative transfer engine using the newly developed vector module for polarization (*Bourassa et al.*, 2008; *Zawada et al.*, 2015; *Dueck et al.*, 2016). The output of SASKTRAN-HR gives the Stokes vectors for the radiance in the model reference frame, which are then rotated into the instrument's coordinate system (see section 2.4.5). Once rotated, the polarization signal required to match the ALI measurement is the vertical polarization given by

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|  | (5.4) |

where and are Stokes parameters defined by and . The variables and are the horizontal and vertical component of the electric field in the instrument reference frame.



**Figure 5-9**: (a) The black, blue, red curves represent the measurement vector, , first term of Equation 5.5, and second term of Equation 5.5 using image 208 (b) A collection of all of the measurement vectors at 750 nm during the mission with a SZA less than 90◦. (c) Image 208 measurement vector with associated error represented by the shading.

The relative radiance measurements from ALI are used to create measurement vectors, , as specified in *Bourassa et al.* (2012b) in the form,

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| --- | --- |
|  | (5.5) |

where is the measured relative radiance from ALI at an altitude and is the relative radiance at a high reference tangent altitude where there is little aerosol contribution. For the ALI measurements, the highest possible tangent altitude where the signal is above the noise threshold is approximately 30 km tangent height and typical values for were between 27 and 30 km. The second term in Equation 5.5 uses modeled radiances from SASKTRAN-HR with only the molecular atmosphere to approximately remove the Rayleigh signal. This is done to improve the speed of the convergence of the retrieval (*Bourassa et al.*, 2012b). Figure 5-9a shows the measurement vector from a 750 nm image (number 208) from the center column of the CCD. The final measurement vector, **,** is shown in the black, with the first term of Equation 5.5 in blue and the second term in red. Removing the Rayleigh component of the signal from the measurement vector increases the sensitivity to aerosol, which increases the speed of convergence of the solution. All of the measurement vectors for the 750 nm images from the mission can be seen in Figure 5-9b.

An initial guess state, , for the aerosol extinction and an assumed particle size distribution profile are set in the SASKTRAN-HR model. The forward model vector is then constructed similarly to the measurement vector, and used in combination with the measurement vector to update the aerosol extinction coefficient profile using the MART algorithm,

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| --- | --- |
|  | (5.6) |

where is the aerosol extinction at each model altitude, and denotes a tangent altitude from the measurements. The forward model result is defined by and the weighting matrix, , relates the importance of each element of the measurement vector to each retrieval altitude. It should be noted that this inversion technique is computationally efficient as it allows for the updating of the atmospheric state without calculating the Jacobian (*Degenstein et al.*, 2009). This iterative process is run until the solution has converged and the value of the summation is approximately one and the final aerosol state is determined.

A precision estimate is also required for the retrieved aerosol profiles, and an uncertainty estimate on the measurement vector is performed. To yield the uncertainty on the measurement vector at a specific tangent altitude, , Equation 5.5 is differentiated and terms are summed in quadrature yielding the following result

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|  | (5.7) |

However, the only uncertainty that is considered here is due to the measurement and calibration errors and systematic biases from the SASKTRAN-HR model are ignored. Since the Rayleigh components are modeled, they are dropped from the uncertainty, simplifying the above result to

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|  | (5.8) |

An example of the uncertainty on a measurement vector for image 208 is located on Figure 5-9c.

Once a retrieval has been completed for a measured radiance profile, the result and the uncertainty estimate is then used to estimate the precision in the retrieved extinction. For each altitude, a gain matrix is defined as

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|  | (5.9) |

where is the change in the retrieved aerosol extinction and is the change in the measurement vector. The gain matrix is calculated through successive numerical perturbation of the measurement vector and re-retrieval (*Rodgers*, 2000). A much faster method is to use the Jacobian to determine the uncertainty has been performed (*Bourassa et al.*, 2012a), but makes an assumption that the gain matrix is equal to the inverse of the Jacobian, as typically the averaging kernel is close to the identity matrix. However, this method adds additional uncertainty to the precision estimate and was deemed unsuitable for the balloon campaign. Instead, with a limited set of balloon data, it is feasible to calculate the gain matrix directly. The uncertainty at each retrieved altitude is then given by

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|  | (5.10) |

where is the covariance matrix of the measurement vector and is the covariance of the retrieved aerosol profile (*Rodgers*, 2000). The covariance matrix is given by

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|  | (5.11) |

where the individual terms are given by

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|  | (5.12) |

The reported precision for ALI aerosol extinction retrievals is the square root of the diagonal of .

Ideally, the ALI measurements would be used independently to also retrieve ozone in the Chappuis band (600-700 nm range for ALI). However, due to the spectral range of the prototype, only a small fraction of the long wavelength side of the absorption band was captured. For this analysis, we have not retrieved the ozone profile but have set the ozone profile in SASKTRAN-HR to an average of the five closest coincident ozone profiles measured by OSIRIS at the ALI location and time. The ozone cross sections were determined by *Burrows et al.* (1999). The surface albedo used is also from the OSIRIS scans since the two instruments share a similar measurement method and should determine a similar albedo for the cloudy conditions. Preferably, albedo would be determined from ALI following the method of *Bourassa et al.*, 2012b, however due to the lack of an absolute calibration this was not possible.

## 5.3.2 Particle Size Retrieval Methodology

Work done by *Rieger et al.* (2014) has shown that different particle size distributions can affect the aerosol measurement vectors, thus yielding some sensitivity to the distribution. In this study, they used an OSIRIS geometry and calculated the respective measurement vectors for a series of particle sizes. This is recreated in Figure 5-10. In panel A, three different log-normal distributions were used to calculate the measurement vectors using a simulated atmosphere through SASKTRAN. The three profiles were: a single fine mode particle size distribution with a mode radius and width of 0.08 µm and 1.6 respectively shown in blue, bimodal particle size distribution that simulates volcanic conditions with the mode radius and width of 0.08 µm and 1.6 for the fine mode and 0.4 µm and 1.2 for the coarse mode, which is shown in black, and lastly the red curve is a representative size distribution with mode radius and width of 77 µm and 1.75. Panel B shows the measurement vectors calculated with the three distributions across a series of wavelengths. The third panel, panel C, shows the difference of the measurement vectors compared to the bimodal distribution. Sensitivity to particle size is only seen past 800 nm measurements but great sensitivity does not occur until measurement are recorded out to 1200 nm. Furthermore, a 1% error in the radiance yields a relative error in the bimodal distribution measurement vector shown by the gray shading in panel C.

For ALI, measurements were only gathered between 650 and 950 nm in wavelength, due to the low sensitivity of the CCD camera in the NIR. As such, it is not be possible to determine both the mode radius and mode width of an assumed log-normal distribution. Instead, the data from ALI was used to determine an Angström exponent, which is essentially one piece of information about the particle size distribution. The Angström exponent is an approximation to the Mie scattering solution where the value of the Angström exponent, , is related to the spectral change in scattering cross section, which depends on particle size (*Angström*, 1964):

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| --- | --- |
|  | (5.13) |

Lower Angström exponents correspond to larger particle sizes and vice versa for small particle sizes. Thus the relation between retrieved extinction at various wavelengths can be used to gather an understanding of aerosol particle size in the form of Equation 5.13, where is the aerosol concentration, and is the scattering cross section, and their product is the extinction coefficient. An example of how the scattering cross section changes with particle size is shown in Figure 5-11 for the 750 nm wavelength where the Mie scattering cross section was calculated for a variety of mode radii and widths.



**Figure 5-10**: Reproduced from Figure 4 of *Rieger et al.* (2014). For OSIRIS scan 6432001 aerosol measurement vectors were calculated at 22.5 km. (A) The three size distributions used in the study. (B) The measurement vectors calculated via the SASKTRAN simulation (C) The relative percent difference of the fine and representative distributions with respect to the bimodal distribution. A 1% error is the radiance yields an uncertainty in the bimodal measurement vector shown by the grey shading.

Since the ALI measurements observe essentially the same atmosphere over the time of one complete spectral imaging cycle (one set of images from 650 to 950 nm), the particle size should be essentially the same for each imaged wavelength. The Angström exponent can then be determined by fitting a line through a series of spectral points in retrieved extinction by rearranging Equation 5.13 into the following

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|  | (5.14) |

The rearrangement demonstrates that the Angström exponent is a slope, i.e. the log of the extinction over the log of the wavelengths.



**Figure 5-11**: Mie scattering cross section at 750 nm computed with the optical properties of the SASKTRAN-HR engine. This variation of the cross section with respect to the mode radius and width allows for some determination of the particle size distribution through the Angström exponent.

Using the retrieved extinction profiles for the complete spectral range, we have attempted a determination of the Angström exponent using a method similar to that outlined by *Rault and Loughman* (2013) for the OMPS-LP analysis. In this method, the independently retrieved extinction profiles at each wavelength and altitude are fit with a straight line in log-wavelength, log-extinction space using a least squares fit. The slope of this line corresponds to the Angström exponent. This is then used to find the best match to the spectral dependence of the Mie scattering cross section in order to update the particle size distribution. With only one piece of information, the mode-width of the log-normal distribution is fixed to 1.6 and the mode radius is updated. The extinction retrievals are then performed again at each wavelength and the process is iterated until the Angström exponent, corresponding to the determined mode radius, converges.

A precision estimate was also required for the Angström exponent. The method used is the standard method to calculate uncertainty from the least squares fit (*York*, 1966). Assuming no uncertainty in the measurement points, the error in the slope is given by

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|  | (5.15) |

where is

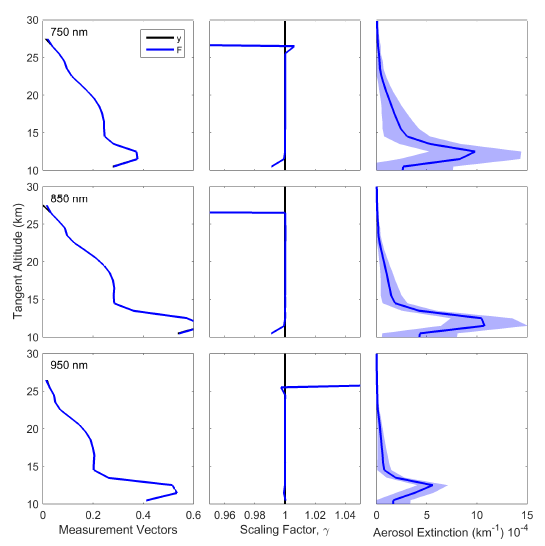
|  |  |
| --- | --- |
|  | (5.16) |

and , , and are the sum of squares of the wavelength, aerosol extinction, and cross term between the wavelength and aerosol extinction and is the number of points. However, there is an associated error with each aerosol extinction profile as outlined in section 5.3.1. So to determine the precision of the Angström exponent, accounting for the uncertainty in the aerosol extinction, a Monte Carlo method was used. The uncertainty of the Angström exponent was calculated millions of times and for each calculation a random amount of the error from the known range was added to the extinction. Finally, the mean from all of the uncertainty calculations of all of the least squares fits was used as the precision estimate on the Angström exponent.

## 5.3.3 Aerosol Extinction Retrievals

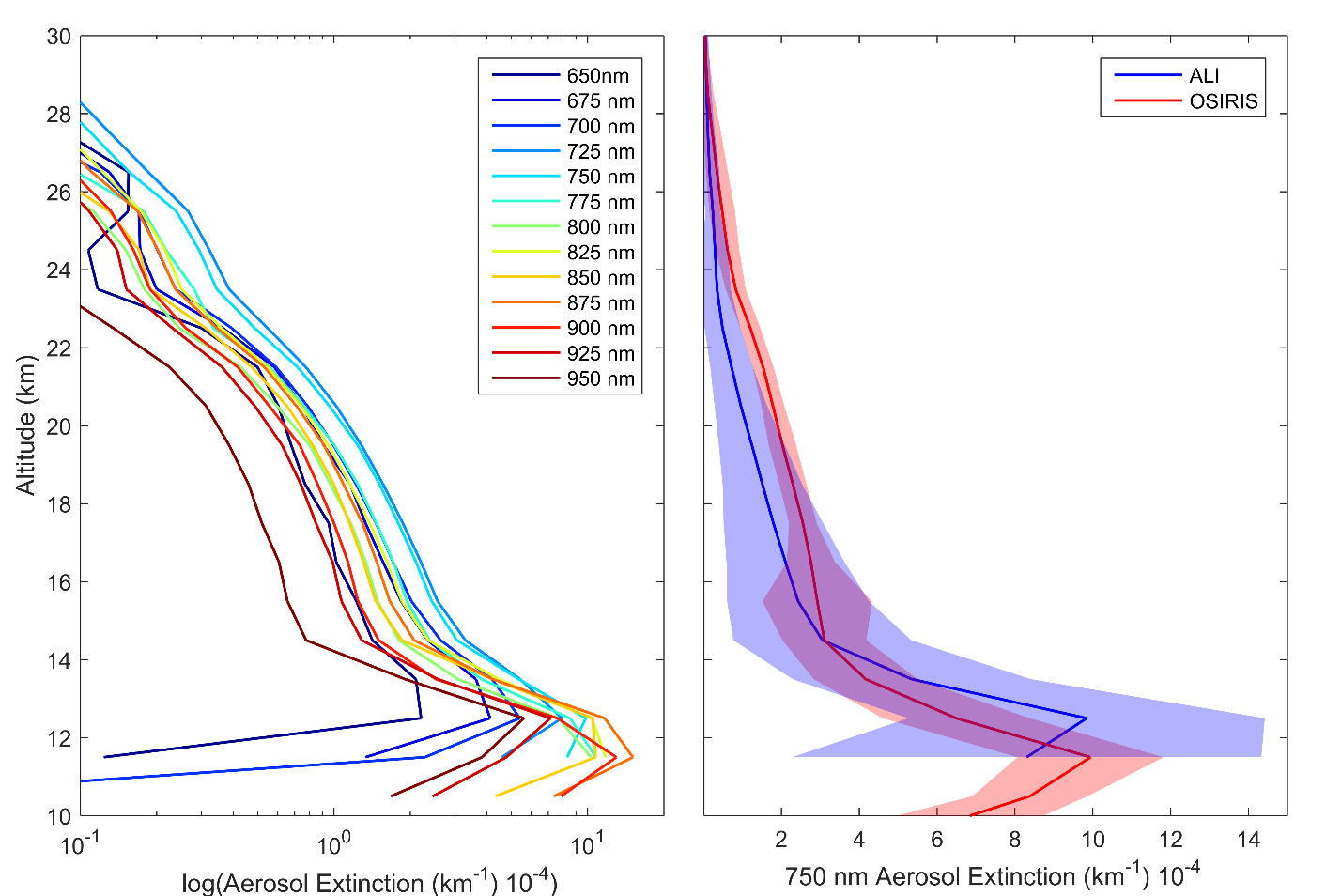
The complete flight data set consisted of 216 image pairs that were recorded in illuminated conditions. The MART retrieval method was performed on a select complete cycle for the purpose of the analysis, specifically the set of images from 204-216 over the wavelength range of 650 to 950 nm. For the purpose of the retrieval an *a priori* particle size distribution was used with a mode radius of 0.08 µm and a mode width of 1.6 (*Deshler et al.*, 2003). A sample of the retrievals can be observed in Figure5-12 which shows the 750, 850, and 950 nm retrievals. The left panels show the measurement vector from ALI in black with the calculation of the measurement vector using 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 extinction to be retrieved in those regions. Instead, the scaling factor, , given by the summation term in Equation 5.6 is scaled to the aerosol profile above and below the last retrieved point to keep the aerosol profile smooth, as discontinuities are non-physical. The middle panel shows the convergence between the measurement vector and the forward model result. The right column of Figure 5-12 is the retrieved aerosol profiles in blue with the associated uncertainty calculated using the method described in the previous section.

The retrieved aerosol extinction profiles for the analysis cycle can be seen in the left panel of Figure 5-13, note the log scale. For the full range of wavelengths, a difference of less than 2% between the measurement vector and forward model is seen throughout the retrieval altitude from approximately 13 to 29 km. Note the behavior of decreasing extinction with increasing wavelength as expected due to the dependence of the cross section with respect to particle size.



**Figure 5-12**: An example of three aerosol retrievals from images 206, 208, and 214, with center wavelengths of 750, 850, and 950 nm respectively are vertically displayed in the figure from top to bottom. The left column shows the measurement vector, , in black with the retrieved forward model, , in blue. The center column shows the ratio of the measurement vector over forward model known as and is the scaling factor between the ALI measurement and the forward model. For both of the first two columns, the black line is barely visible due to the very good agreement of the forward model. The final column is ALI aerosol extinction in blue with the associated error represented by the light blue shading.

The ALI 750 nm aerosol extinction profile is shown in the right panel of Figure 5-13 with the shading representing the precision of the retrieval. The error is strictly based on measurement and instrument uncertainty and neglects any model and atmospheric state uncertainties as previously outlined. The red curve is the average 750 nm aerosol extinction profiles of the same five coincident OSIRIS scans used for the ozone profile. The retrieved extinction profiles from ALI and OSIRIS are within the total retrieval uncertainty. It is encouraging that the instruments follow the same overall profile shape including the stratospheric layer and the steep increase below 15 km. Aerosol is notoriously difficult to validate in remote sensing with various technique and instrument geometries, and yet the SAGE II, SAGE III and OSIRIS differences are generally below 20-30% up to 30 km (*Bourassa et al.*, 2012b; *Rieger et al.*, 2015). However, the comparisons between the OSIRSI and ALI are acceptable. There are also several possible systematic errors not accounted for in the inversion including the choice of retrieval altitude ranges, particle size composition and distributions, stray light, and the high altitude aerosol load.



**Figure 5-13**: Left is the retrieved aerosol extinction profiles from the last complete imaging cycle consisting of images 205 to 216 from the 0.0◦ horizontal line-of-sight. Right is the 750 nm ALI aerosol extinction in blue with its error represented by the shading compared to the 750 nm extinction measured by OSIRIS in red with its error represented by the shading. Originally published as Figure 12 in *Elash et al.* (2016).

As a further note, other issues may have resulted in the disagreement between OSIRIS and ALI, mainly the estimation of the albedo and pointing inaccuracies. For the albedo, vertically linear polarized aerosol retrievals have a much larger sensitivity to albedo. For a scalar retrieval, changing the albedo from zero to one results in approximately a 30% increase in the aerosol extinction, but for a linear polarized measurement this change in albedo can be as large as a 100% increase in aerosol. The retrieval was performed again on image 208 using an albedo of zero and one and the results shown in Figure 5-14a. Once again, note the log scale. The albedo used from OSIRIS was 0.79. It should be noted that increasing the albedo higher than the OSIRIS values does not greatly increase the aerosol extinction. However, the retrieved aerosol profile varies by almost a factor of two just from a change in albedo. A similar reanalysis was performed using the error in the zenith pointing discussed in section 5.2. The results of the alteration of the pointing can be seen in Figure 5-14b. From decreasing the zenith angle, the aerosol extinction is increased which could account for the largest discrepancies between the OSIRIS and ALI results at the 20 km range, but moves the aerosol peak to a higher altitude causing a further discrepancy with OSIRIS at lower tangent altitudes. However, due to a lack of pointing information from the gondola this is the best estimation that could be performed.

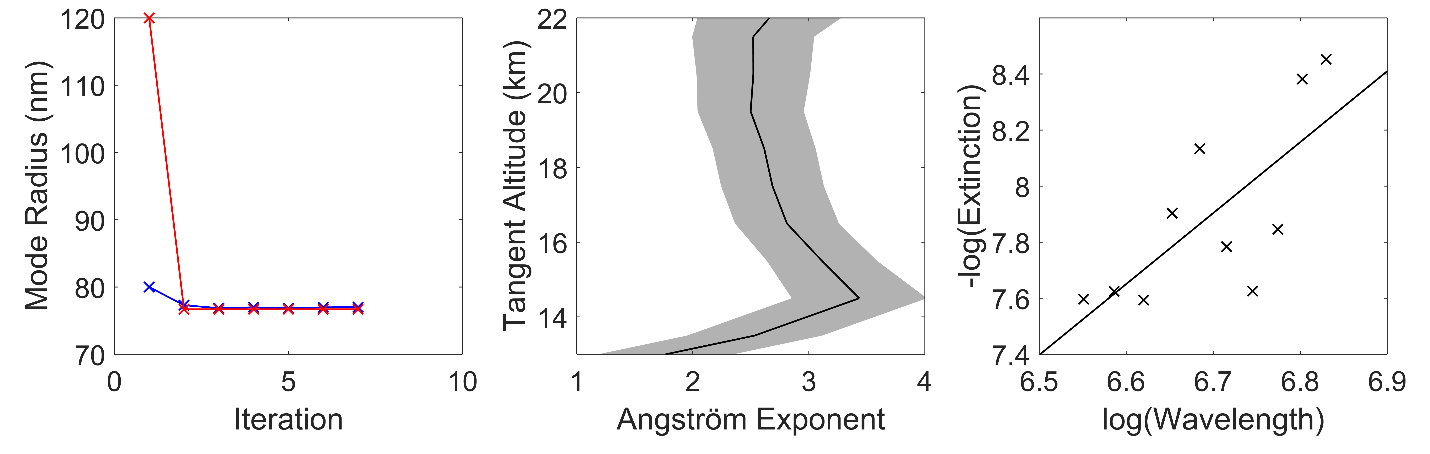
Another source of systematic error could arise from sensitivity to the solar scattering angle in the retrieval algorithm due to the relationship between particle size distribution and the scattering phase function. For the ALI image the solar scattering angle is 98◦ and for the five OSIRIS scans they are 77◦, 89◦, 90◦, 91◦, 92◦, and 93◦. With the exception of the forward scatter angles of 77◦ and 89◦ from OSIRIS, the scattering angles between OSIRIS and ALI are similar and should not cause a large effect on the retrieved profiles. However, as noted from the study detailed in Chapter 6, a strong sensitivity to particle size distribution occurs near solar scattering angles of 90 degrees for the vertical polarized measurements. Regardless, the comparison of the OSIRIS and ALI results are encouraging.



**Figure 5-14**: (a) Image 208 (750 nm) re-retrieved using an albedo of 0 and 1 compared to the original albedo used from OSIRIS. (b) Using the determined zenith pointing error from section 5.2, image 208 is retrieved again using the maximum possible pointing error compared to the original.

## 5.3.4 A Sample Particle Size Retrieval

The particle size method outlined above to determine the Angstrom exponent was also applied to this measurement set consisting of images 204 to 216. The retrieved extinction at a given altitude was rejected from the straight line fit if the converged forward model radiance at that altitude was not within 2% of the measurement vector. In the case shown in right of Figure 5-15, at the 14.5 km altitude point, only 10 of the 13 possible wavelengths contributed to the determination of the Angström exponent. The left panel of Figure 5-15 shows the median Angström exponent that was determined after each iteration and convergence can be seen after a couple iterations. The results are shown in the middle panel of Figure 5-15, where the Angström exponent is between 2 and 3 throughout the altitude range from 13 to 22 km. Assuming a mode width of 1.6 yields a median mode radius of 0.077 µm. In comparison to typical levels of background aerosol from the Laramie, Wyoming OPC data (*Deshler et al.*, 2003), the retrieved particle size parameters are certainly within the expected range, although there is a relatively large error bar on the retrieved value, limiting the usefulness of the retrieved particle size information for background aerosol. However, with these error bars, even this limited spectral range would have the sensitivity to detected particle size changes as seen by OSIRIS and SAGE II over recent decades due to small volcanic perturbations (*Rieger et al.*, 2014).



**Figure 5-15**: The left panel shows the convergence of two sample particle size retrievals, blue and red represent an initial state of 0.08 and 0.12 µm mode radius respectively. Both initial states converge to the same value over approximately 3 iterations in the particle size retrieval method. The middle panel shows the final Angström exponents determined from images 204-216. The shading represents the error associated with the least squares fit. The right panel shows a typical least squares fit of the retrieved extinction values over wavelength to determine the Angström exponent at model altitude of 14.5 km. Originally published as Figure 13 in *Elash et al.* (2016).

1. Portion of sections 5.1.1, 5.2, 5.3.1, 5.3.3, 5.3.4 and 5.4 as well as Figure 5-3, Figure 5-6, Figure 5-7, Figure 5-8, Figure 5-13, and Figure 5-15 were originally published in *Elash et al.* (2016) [↑](#footnote-ref-1)