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

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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.

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

After the successful post-flight recovery of ALI was unpacked and check for any damages in Saskatoon, SK on September 25, 2014. No obvious damage had occurred to ALI from the fight and the instrument was functioning correctly. 216 raw aerosol mode images were obtained from the flight and calibration was performed including pointing alignment and the calibrations as detailed in Section 3.3.

The images needed to have complete pointing information added to the images, the raw images only had position and altitude information from the onboard GPS. The azimuth and zenith directional information needed to be added to the images as they are needed to determine the line of sight of each pixel on the CCD. The CNES team supplied the SAA information from the flight and was correlated to the images using GPS time. However, no information was supplied about the zenith direction of the gondola, we were just notified that the gondola was zenithally stable throughout the entire flight. So some manual calibration of the zenith angle occurred. ALI was tilted at 3o so the zenith as assumed to be 93o for ALI. This starting guess was not accurate enough since features in the radiance profiles did not retain the same altitude over the course of a few images. To determine a more precise zenith angle, the zenith angle was varied from 92o to 94o in 0.1o intervals and the tangent altitude was calculated for each case. Then the radiance profiles for each zenith angle was compared to find zeniths where the features were align. The zenith angle with the optimal alignment was determined to be 92.55o with an uncertainty of 0.10o.

The calibration techniques discussed in section 3.3 were then applied to the raw images to find the final radiances. As an example image number 208 is used to demonstrate the steps in the calibration on a flight image. Image 208 is a 750 nm taken at 13:57 UTC with a solar zenith angle and solar scattering angle of 63o and 98o respectively. The dark current and DC offset have been removed form image 208 using the Equation 3.42. 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 seen. Finally, a flat fielding calibration is performed (see section 3.6.5) and a final calibrated image can be seen in Figure 5-6a. Remember that no absolute calibration was performed on ALI, so the radiance are relative radiance in arbitrary units to the 775 nm laboratory calibration. 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, 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.



**Figure 5-5:** Stray light removal technique is 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 48.55oN, 80.00oW with a solar zenith angle and solar scattering angle of 63o and 98o respectively. (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.

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. 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 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 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. 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 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.



**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 solar zenith angle is greater than 90o and solid lines are profile where the solar zenith angle is less than 90o.

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 has 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 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.



**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 90o in the azimuth from the sun facing southwards. These spectral profiles are presented at several tangent altitudes with a horizontal look direction of 0o. The shading represents the error on the radiances.

# 5.3 Aerosol Retrievals

Test

## 5.3.1 Aerosol Extinction Retrieval Methodology

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## 5.3.2 Aerosol Extinction Retrievals

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## 5.3.3 Particle Size Retrieval Methodology

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## 5.3.4 A Sample Particle Size Retrival

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# 5.4 Results

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