LIST OF FIGURES

Figure page

**Figure 2-1**: Sample log-normal distribution for typical non-volcanic stratospheric aerosol. 12

**Figure 2-2**: Bimodal particle size distributions fits from OPC. (a) Distributions from a volcanic period after the Mount Pinatubo eruption recorded in 1993. (b) Distributions from a background aerosol period recorded in 1999. Both of the aerosol distribution measurement are from 20 km altitude with the solid line being the fine mode and the dashed line is the coarse mode. Figure is recreated from Figure 5 of *Deshler et al.* (2003). 13

**Figure 2-3**: An occultation instrument monitoring the atmosphere by scanning the atmosphere by looking directly at the sun. 17

**Figure 2-4**: Lidar instrument showing measurements in both the nadir and off-nadir lines of sight. 18

**Figure 2-5**: Limb scattering geometry measurement for an instrument where single and multiple scattering events occur. 20

**Figure 2-6**: (a) Change in extinction for Rayleigh and Mie scattering over wavelength. The Mie scattering uses a log-normal distribution with a mode width of 1.6 and a mode radius of 0.08 µm. (b) The first term of scattering matrix, , for Rayleigh and Mie scattering cross scattering angle. 31

**Figure 3-1**: Geometry for the AOTF wave derivation assuming the acoustic wave is along the x-axis and the AO interaction occurs along the z axis over an interaction length, . The parameters , , and are the position vector, wave vector, and angle of the incident electric field and similarly for the diffracted electric field. Figure recreated from *Xu and Stroud* (1992) 41

**Figure 3-2**: A standard non-collinear AOTF experiential set up. The crystal is assumed to be infinitely long in the y direction. Figure recreated after *Guenther* (1990) number 14B-1. 47

**Figure 3-3**: General Layout of an AOTF. A randomly polarized incoming light source hits the front surface of the birefringent crystal. The black bar below the crystal is the piezoelectric transducer that produces the RF signal and forms the acoustic wave represented by the grey arrow. The momentum matching Bragg diffraction occurs and monochromatic polarized light (-1 order) exits the AOTF at a constant angle with the 0th order and +1 order being blocked by an optical stop. 47

**Figure 3-4**: The wave vectors generated by the AOTF experiment set up in Figure 3-2. From the above figure and are the wave vectors of the extraordinary and ordinary axis of the AOTF crystal. Originally published as Figure 1 in *Elash et al.* (2016). 49

**Figure 3‑5**: (a) An AOTF undergoing Bragg diffraction with an unpolarized input incident wave with a RF wave applied represented by the arrow. After the diffraction event four output signals are formed: the zeroth order and first order ordinary (o) and extraordinary (e) signals. However the only optical path that remains at a constant angle no matter the applied RF wavelength is the first order extraordinary diffracted signal. (b) Two linear polarizers are added to the system, the first linear polarizer removes the ordinary polarization from the outputs with the dotted lines and the second linear polarizer removes undiffracted extraordinary light shown by the dashed line. This configuration is the “AOTF-on” state. (c) The system in (b) without a RF wave so no Bragg diffraction is occurring. Once again the first linear polarizer removes the ordinary polarization represented by the dotted line and the second linear polarizer removes the extraordinary light shown by the dashed line. This configuration is the “AOTF-off” state. Originally published as Figure 2 in *Elash et al.* (2016). 52

**Figure 3-6**: A standard paraxial ray tracing diagram. The aperture is located to make the system telecentric in the image plane and is the focal length of the lens. 53

**Figure 3‑7**: Ray Tracing diagram simulation of the telecentric lens system preformed using Code V. The elements in the system are the following: (1) Optical Stop and telecentric aperture. (2) 100 mm focal length plano-convex lens. (3) Brimrose AOTF. (4) 100 mm focal length plano-convex lens. (5) Telecentric Aperture. (6) 75.6 mm focal length plano-convex lens. (7) Imaging plane. It should be noted that the x and y scales are not the same in this image. Also, in the lab a polarizer is added in front and behind the AOTF as well as prisms after the AOTF. 54

**Figure 3-8**: Quantum efficiency of the Kodak KAF-1603ME contained within the QSI CCD camera is represented by blue curve. Quantum efficiency provided by QSI Scientific. (http://www.qsimaging.com/616-overview.html) 56

**Figure 3-9**: The effect on the optical path of converging light bundles as they pass through a material of index of refraction . When the index of refraction strongly depends on wavelength, as in the AOTF, the optical path length can experience great changes that alters the focal point of the system. 57

**Figure 3-10**: Code V simulation of the spot size for the telecentric system at focus at 800 nm. The spots are shown for 0.0, 1.5 and 2.6 degree fields of view at 600 nm (blue) and 800 nm (green). The full spot sizes for the 600 nm spots are 0.16, 0.22, and 0.25 mm for 0.0, 1.5, and 2.6 degrees fields respectively, with the corresponding 800 nm spot sizes being 0.024, 0.053, 0.094 mm. The black circles represent the Airy disk for each specific wavelength and FOV. 58

**Figure 3-11**: The top left is the original test image used for the telecentric experiment. The top right, bottom left, and bottom right are the images recorded through the telecentric system at 650, 750, and 850 nm. The system is focused at 800 nm. 60

**Figure 3-12**: Ray Tracing diagram of the telescopic lens system simulated by Code V. The elements in the system are the following: (1) 100 mm focal length plano-convex lens. (2) Location where field stop is located to limit stray light (3) 100 mm focal length plano-convex lens. (4) Brimrose AOTF. (5) 75.6 mm focal length plano-convex lens. (6) Imaging plane. It should be noted that the x and y scales are not the same as Figure 3‑7. Also, in the lab a polarizer is added in front and behind the AOTF as well as prisms behind the AOTF. 61

**Figure 3-13**: Vertical displacement of a collimated bundle of light cause by a material of index of refraction . 62

**Figure 3-14**: Code V simulation of the spot size for the telescopic system. The spots are shown for 0.0, 1.5 and 3.0◦ fields of view at 600 nm (blue) and 800 nm (green). The full spot sizes for the 600 nm spots are 0.004, 0.045, and 0.122 mm for 0.0, 1.5, and 3.0◦ fields respectively, with the corresponding 800 nm spot sizes being 0.096, 0.081, 0.047 mm. The black circles represent the Airy disk for 600 nm wavelength and each FOV. 64

**Figure 3-15**: The top left is the original test image used for the telescopic experiment. The top right, bottom left, and bottom right are the images recorded through the telescopic system at 650, 750, and 850 nm. The system is focused at 800 nm. 65

**Figure 3‑16**: Final optical design for ALI with a Code V ray tracing diagram. The elements in the system are: (1) 150 mm focal length plano-convex lens. (2) Field stop. (3) 100 mm focal length plano-convex lens. (4) Vertical (extraordinary) linear polarizer. (5) Brimrose AOTF. (6) Horizontal (ordinary) linear polarizer. (7) 50.4 mm focal length bi-convex lens. (8) Imaging plane. Originally published as Figure 4 in *Elash et al.* (2016). 66

**Figure 3-17**: MTF analysis performed by Code V for the final ALI design used in the balloon campaign. The 7 pixel running average corresponds to a spatial frequency of 15.5 cycles/mm. 68

**Figure 3-18**: The final optical layout of ALI's optical chain from the top and profile perspectives with the components being the following: (1) 150 mm plano-convex lens with 25.4 mm diameter. (2) Field Stop. (3) 100 mm plano-convex lens with 50.8 mm diameter. (4) Optical rail system. (5) Vertical (extraordinary) linear polarizer. (6) Brimrose AOTF. (7) Rotation Stage. (8) Horizontal (ordinary) linear polarizer. (9) 50 mm bi-convex lens with 25.4 mm diameter. (10) QSI 616s CCD camera. (11) Optical rail. 75

**Figure 3-19**: The custom mounting hardware design to mount the AOTF and QSI CCD camera into ALI's opto-mechanical design. Left: Custom AOTF mounting hardware. Right: The five piece QSI CCD camera mounting hardware. 76

**Figure 3-20**: ALI opto-mechanical system with three degree horizontal tilt and designed baffle discussed in section 3.4.2. Originally published as Figure 5 in *Elash et al.* (2016). 76

**Figure 3-21**: (a) Start of the optical baffle geometry method. The red lines are the marginal rays and the green line is the first ray that can enter the system without encountering at least three surfaces. (b) The first internal vane has been added and the location of the next vane is being determined. (c) The second internal baffle has been added and since the green line intersects with the critical baffle no more baffles are required. (d) Additional interior vanes and an external vane have been added to ensure a height to pitch ratio of 0.5 to improve the baffle’s capabilities to reduce stray light. 79

**Figure 3-22**: A cross-section view of the ALI baffle system. All dimensions on the drawing are in millimeters and the sloped black lines represent the 6 degree FOV. 80

**Figure 3-23**: ALI baffle vain profile. Dimensions are in millimeters. 81

**Figure 3-24**: Final ALI optical and opto-mechanical assembly. 81

**Figure 3-25**: ALI optical system with light tight case attached. Three degree horizontal tilt not present in this image. 82

**Figure 4-1**: A complete flow diagram showing interaction between all the of ALI software modules on board the ALI flight computer. 86

**Figure 4-2**: Telecentric test experiential setup for AOTF parameter determination. All lenses and apertures are represented by the vertical lines. 90

**Figure 4‑3**: (a) A row averaged image taken from the AOTF of the point spread function when the tuning frequency of the AOTF was at 124.96 MHz. (b) The FWHM for each of the determined wavelengths for the AOTF. The FWHM at 600 nm is 1.5 nm and as the wavelengths get longer the FWHM increases to 4.9 nm at 1080 nm. (c) The calibration curves for the AOTF RF versus the diffracted wavelength which contains the data points recorded and fit curves. (d) The percent error with respect to the measured frequency for the two best fit curves in the previous panel. Originally published as Figure 6 in *Elash et al.* (2016). 91

**Figure 4‑4**: Simulated scalar radiances from the SASKTRAN-HR in blue and red with the radiance on the left side and the scaling factor in black with the value on the right side. 95

**Figure 4-5**: The DC offset curve (Equation 4.5) is seen in black where the lab and flight calibration data is shown in blue. The counts on the vertical axis are the counts that need to be removed to account for the DC offset. 97

**Figure 4-6**: The dark current from the calibration images over a series of camera temperatures and exposure times. 98

**Figure 4-7**: A calibration image after stray light removal has been performed where the measured wavelength is 750 nm with a 1 second exposure time. Vignetting can be seen as moving away from center of the image. Additionally the last 1◦ of the horizontal FOV on the right side is lost due to strong contamination from reflections within the system. Originally published as Figure 7 in *Elash et al.* (2016). 99

**Figure 4-8**: The blackbody emittance curve from Equation 4.6 normalized to 775 nm. 101

**Figure 4-9**: The flat fielding coefficients for 750 nm. 102

**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. 107

**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. 108

**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). 110

**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. 111

**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. 115

**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). 116

**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). 117

**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). 118

**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. 120

**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. 125

**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. 126

**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. 129

**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). 130

**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. 132

**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). 133

**Figure 6-1**: (Top) The fraction of a linear polarization (left is horizontal and right is vertical) over the total radiance for molecular air density. (Bottom) The change in the fraction of linear polarization between an atmosphere that contains aerosol and one with only molecular air density. 139

**Figure 6-2**: The two aerosol profiles used in this study. The blue is a background aerosol extinction levels, and the red curve is a representative aerosol profile after the Nabro eruption. 142

**Figure 6-3**: Percent differences between the vector retrieved aerosol extinction profiles and the scalar retrieval from simulated total radiance measurements. Each column represents a different particle size distribution (see Table 6-1). 148

**Figure 6-4**: (Top) For a horizontal (left) or vertical (right) linear polarization the percent of the signal that is attributed to aerosol, . (Bottom) The change in the fraction of the limb signal due to aerosol when compared to the total radiance for the horizontal (left) and vertical (right) polarization (). The simulation uses a geometry of SZA=45◦ and SSA=60◦, with the albedo being 0 and the aerosol state the background profile with particle size distribution 1. Take note the red-blue scale is non-symmetric. 150

**Figure 6-5**: Dependence of the fraction of the limb spectra due to aerosol on solar scattering angle (left panels) for total radiance (top), horizontal polarization (middle) and vertical polarization (bottom), and the magnitude of the radiance for each case (right panels). Note the low signal near SSA of 90 degrees for the vertical polarization which would be problematic for terminator orbits. 151

**Figure 6-6**: The ratio of the linearly polarized radiance to the total radiance for horizontal (left) and vertical (right) orientations. Note that the scale for each plot is different. The simulation was performed with a SSA of 60 degrees with volcanic aerosol loading for a tangent altitude of 20 km. 152

**Figure 6-7**: The mean percent difference between the retrieved aerosol extinction profile with an assumed particle size distribution and the true state corresponding to the indicated particle size distribution (see Table 6-1). Error bars represent one standard deviation of the variability across all viewing geometries. Results shown are for 750 nm and 20 km altitude. 155

**Figure 6-8**: The wavelength dependence of the co-variance for the horizontal and vertical polarization retrievals normalized to the total radiance case. The faded line represent one standard deviation of the variability encountered across all input parameters. The top panel is for an instrument design and/or operation that compensates for changing signal levels with polarization and viewing geometry, and the bottom panel is for uncompensated measurements. 157

**Figure A-1**: The transmission and extinction ratios of the LPVIS100 used in ALI. 184

**Figure A-2**: Typical Spectral response of a Synapse CCD Detector as provided by Jobin-Yvon. 187