CHAPTER 7

CONCLUSION

# 7.1 Summary

Space-based remote sensing measurements of stratospheric aerosol have been performed since the 1970’s, and have provided valuable insight into aerosol process and trends, including a key record of the “persistently variable” effect of volcanic eruptions. Due to their impact on climate through the scattering of incident solar radiation back to space, the continued monitoring of stratospheric aerosol is critical (*Solomon et al.*, 2012). However, there are very few operational or even planned satellite missions with stratospheric aerosol measurement capability, and the scientific requirements for further understanding the transport of both anthropogenic and volcanic aerosol source gases into the stratosphere present challenges in terms of spatial resolution and coverage of the measurements.

In this thesis, the design, test flight and first results from a new prototype satellite instrument specifically tuned for stratospheric aerosol measurement was presented. The Aerosol Limb Imager, or ALI, instrument was designed to capture hyperspectral images of limb scattered sunlight to determine aerosol extinction and particle size information. The hyperspectral imaging nature of the instrument provides the capability to measure both in altitude and in the cross-track horizontal dimension. Global coverage of the stratosphere can then be obtained by successive measurement along the satellite track. The limb scattering technique, combined with the hyperspectral imaging design of the instrument, provides a powerful combination of global coverage, high spatial resolution, along with the capability to retrieve high quality stratospheric aerosol information, as proven by the ground-breaking OSIRIS algorithms (*Bourassa et al.*, 2007; 2012). In this work, a prototype version of the ALI instrument was developed specifically for a test flight from a stratospheric balloon. This platform provided low cost access to the space environment, including altitudes that are sufficiently high to image the stratospheric limb, which was the critical factor for this project.

The ALI prototype was designed using an imaging quality, large-aperture AOTF to rapidly filter selected narrow wavelength bands from 650 to 950 nm in two dimensional images of the limb radiance with exposure times on the order of one second. Commercial off-the-shelf components were used for the prototype, consisting of a simple linear optical system with telescopic front-end optics, a focusing lens for the back-end optics, and a scientific grade CCD detector. The system had a large field-of-view of 6◦ to image the entire limb from the ground to the balloon float altitude (approximately 35 km). This field-of-view ws substantially larger than that required for a space-craft version of the instrument owing to the difference in viewing geometries between low earth orbit and stratospheric balloon. This requirement resulted in some optical aberrations in the outer one degree of the field-of-view, a region which was also partially outside of the acceptance angle of the AOTF. From laboratory testing and through simulations in Code V modelling software, the spatial resolution of the instrument was nominally 210 m at the limb tangent point, both in the vertical and horizontal directions, which was well within the sub-kilometre spatial resolution requirement for thin aerosol structures. A systematic calibration of the instrument was performed in the lab, accounting for dark current, stray light, flat fielding, and a relative spectral calibration. An absolute calibration was not performed due the lack of an appropriate lab source; however, ground based testing of the instrument provided an opportunity to compare blue sky measurements of the scattered sunlight radiance with forward model calculations and verify the instrument sensitivity.

The stratospheric balloon test flight for ALI was performed in Timmins, Ontario, from the CSA balloon launch facility. ALI was mounted onboard the CNES CARMEN-2 gondola, and the launch occurred at 05:35 UTC on September 19, 2014, with a flight duration of 16 hours and 14 minutes. From float altitude at 36.5 km, ALI captured 216 two dimensional images of the limb radiance over five hours. Analysis of this hyperspectral data set shows that the measured radiances are of high quality, and show both vertical and horizontal features of the cloud and aerosol layers. These were used to retrieve aerosol extinction coefficient profiles that show reasonable agreement with coincident OSIRIS satellite measurements. Furthermore, rudimentary particle size distribution information was also retrieved from the ALI measurements. Due to the limited spectral range of the prototype, the retrieval of the particle size distribution was noisy, but still yielded sensitivity to the larger perturbations typically seen after a volcanic eruption.

The birefringent nature of the AOTF means that the ALI measurements were of the linearly polarized limb radiance, whereas historically limb scattered sunlight measurements from space use total radiance. While some preliminary work had already shown that stratospheric aerosol information could be retrieved from a measurement of the polarized radiance observed from aircraft (*McLinden et al.*, 1999), this is a significant difference from previous generations of space-craft instruments and a thorough, systematic study of the potential impact of this change was performed as part of this work. The results of this study show that for most observation geometries and with compensation for the signal levels, there is no disadvantage to these polarized measurements.

# 7.2 Contributions of This Work

The work in this project has provided several contributions to the field of atmospheric remote sensing, through both advancements in technology, and the modelling and algorithm development that are inherently linked to the technological improvements. These contributions are:

* The first sub-orbital demonstration of an atmospheric remote sensing imaging system using ATOF technology. Although *Dekemper et al.* (2012) showed ground-based measurements of a factory emission plume using a custom AOTF-based imager, this is the first successful sub-orbital demonstration of this technology that we are aware of.
* An AOTF-based imager design specifically for aerosol measurements. The spectral sensitivity of the AOTF in terms of range and resolution was essentially a perfect match for the requirements of measuring aerosol using limb scattered sunlight. This work provides the ground-work for a future satellite instrument that leverages the combination of the AOTF technology and the limb scattering remote sensing technique.
* The first retrieval of aerosol extinction profiles and particle size information from 2D hyperspectral images of the limb radiance. Although the retrievals presented here were an adaptation of existing algorithms that use radiance profile measurements from scanning spectrometers, this advancement demonstrates the potential to achieve both vertical and cross-track dimensions from a future satellite-based version of ALI, which would vastly improve upon the existing capability for obtaining global coverage.
* The first study on the impact of measuring the polarized radiance, rather than the total radiance, on the ability to retrieve stratospheric aerosol information from limb scattered sunlight measurement. This is important not only for the future of ALI, but also for other instruments under study and development, notably the Belgian ALTIUS instrument, which also uses AOTF technology and will similarly measure the linearly polarized radiance.

# 7.3 Outlook, Recommendations and Future Challenges

This thesis work has provided for a successful demonstration flight of a prototype ALI instrument, including the foundational hardware design work and scientific analysis of the flight measurements. This success has provided for opportunity to further pursue the ALI as a space-based mission concept for micro- or small-satellite deployment. Recently, the Canadian Space Agency has provided funding through the FAST program to develop a second, higher fidelity prototype, again for stratospheric balloon test flight, but which incorporates several important functional improvements discussed below. In parallel to this, the CSA has also provided funding to Honeywell Aerospace through the competitive Space Technology Development Program in order to perform a design and feasibility study for a satellite version of the ALI instrument, including an advanced optical design suitable for the geometry of low-earth orbit, and all of the thermal and mechanical accommodations required for space flight.

The most important design improvement to ALI from a scientific perspective is the extension of the spectral range. The capability to retrieve particle size information vastly increases with the inclusion of measurements from the 1000 to 1500 nm near infrared spectral range. Although this could be done with a second hardware channel, i.e. a second AOTF and detector designed for this spectral range, it could be elegantly accomplished with two key technological advances: 1) The use of a dual-transducer AOTF with the capability to tune over the entire spectral range, i.e. over more than one octave in wavelength. These are just now becoming commercially available. 2) The use of an extended range “vis-GaAs” detector, also just recently commercially available, to provide good sensitivity across the full visible and near infrared range.

A second important functional improvement to the instrument from a scientific perspective is the capability to measure both orientations of the linear polarization. This would provide a measurement to discriminate between aerosol and cloud particles through the distinct differences in the scattering phase matrix. One could imagine several approaches that would provide this functionality, including a twin hardware channel with the AOTF oriented in the orthogonal direction, or a second set of back-end optics oriented to measure the diffracted beam generated from the other axial direction of the birefringent crystal. A more elegant approach that could be explored involves incorporating an element to actively rotate the selected polarization direction in the front-end optics, by moving a wave plate, or possibly with a voltage-controlled liquid crystal rotator.

For future work involving ALI prototype testing on balloons and possibly aircrafts, several recommendations can be made from the lessons learned in this work.

* Careful attention should be paid to the orientation of the measured polarization and the planned flight geometry to avoid the problematic lack of sensitivity of the vertical polarization for scattering angles near 90 degrees.
* Even with the detailed baffle design and the robust method of removing stray light with the cycling of the AOTF, some stray light was still observed in the obtained images. Impact and mitigation of this should be tackled in future iterations of the instrument. Two design changes could particularly help with this. Glan-Taylor prism polarizers (*Archard and Taylor*, 1948) should replace the nanoparticle linear polarizers. The advantage to the Glan-Taylor prism is rather than attenuate the unwanted polarization it is reflected though total internal reflection approximately 90 degrees from the optical axis where it can be absorbed away from the imaging plane reducing the stray light contamination. Further, the addition of a back-end telescope between the AOTF and the camera could be used to help further separate the desired diffracted signal from the zeroth order beam in physical space to reduce stray light further.
* An absolute calibration would improve the retrieval quality by allowing the direct determination of surface albedo. This is simply a matter of having access to the necessary calibration equipment.
* The addition of a shutter or masked pixels on the detector would be useful to calibrate the temperature dependent DC offset and dark current changes. Additionally, a faster readout would greatly increase the number of measurements that can be made with the system.
* A folded optical design would provide a much easier footprint to accommodate on the gondola and potentially help with thermal considerations by minimizing the size of the optical chain.

All of these improvements will help to improve the image quality, scientific return and ultimately the space feasibility of the ALI instrument.

Overall, the test flight of the ALI prototype developed in this work was a success and provides an important demonstration of the technology in a space environment, which is a key step in the path to a satellite mission. The design concept of matching the novel AOTF capability to the strengths of the limb scattering remote sensing technique makes for an innovative, low-cost approach to high quality, high resolution global stratospheric aerosol measurements. With continued work, ALI has potential to fulfill the aerosol monitoring needs of the future and both continue, and improve upon, this important data record for understanding our changing climate.