CHAPTER 1

INTRODUCTION

The atmosphere of the Earth is a dynamic, evolving system with complex composition. The concentration of various atmospheric species is dependent upon altitude, geographical location, season, and time of day. These species interact with light and absorb, scatter, and re-emit the radiation originating from the sun. Using spectroscopy, concentrations of different species can be determined to discover the composition of the atmosphere. Over a period of time, changes to the composition caused by natural and anthropogenic sources can be used to infer processes and trends, some of which are causes or effects of climate change. One particularly important species in terms of the radiative balance of the Earth is aerosol in the stratosphere. These aerosols are typically submicron-sized droplets of sulfuric acid and water that scatter solar radiation away from earth, effectively increasing the planetary albedo and causing a cooling effect of the surface temperature. Source gasses that form these aerosols can arise from the burning of fossil fuels, biomass burning, and natural marine processes and form a relatively stable layer of aerosol in the stratosphere, often referred to as the “background” layer (*Kremser et al.*, 2016). Large and unpredictable perturbations of this layer occur after large volcanic eruptions that can inject large quantities of sulfur dioxide directly into the stratosphere where it oxidizes and forms aerosol droplets. The variability of the aerosol layer in terms of particle size, composition and its spatial and temporal distributions, makes it both challenging and critical to measure and understand. This so-called “persistently variable” aerosol layer has been linked to a significant reduction in the global-warming from greenhouse gases that would have occurred (*Solomon et al.*, 2011), and have played a role in understanding the “emergence of healing” of the ozone layer in the Antarctic (*Solomon et al.*, 2016).

Instrumentation has been deployed over the past several decades to monitor the atmospheric state from the ground, within the atmosphere, and from orbit using many different methods. As progress is made towards understanding the process and trends in atmospheric composition through these observations, the scientific questions inevitably probe deeper into more detailed and smaller scale structures requiring both high spatial and temporal resolution measurements as well as global coverage. This evolution provides ever more challenging requirements for new measurements and hence new instrumentation to provide these observations. Advancements in optical and detector technology combined with the increasing ease of access to space means that the capabilities of the future generation of satellite instruments will be able to tackle the driving scientific needs for precision, accuracy and resolution with global coverage.

Stratospheric aerosol in particular has been monitored globally from satellite platforms since the 1970s. The “gold-standard” remote sensing method is solar occultation, most notably used by the NASA SAGE (Stratospheric Aerosol and Gas Experiment) (*Russell and McCormick*, 1989; *Thomason and Taha*, 2003) series of satellite missions. Solar occultation instruments directly measure the spectral attenuation of sunlight as it passes through the atmosphere and through this acquire accurate vertical profiles of the aerosol extinction coefficient; however, the occultation technique is inherently limited in the number of observations that can be acquired per day due to the simple fact that the measurement is made only when the satellite instrument observes a sunrise or sunset from orbit. More recently other remote sensing techniques have been used successfully from space to measure stratospheric aerosol. One such technique is the measurement of limb scattered sunlight, which is performed by the Canadian OSIRIS (Optical Spectrograph and InfraRed Imaging System) (*Llewellyn et al.*, 2004) instrument onboard the Odin spacecraft. The observation of limb scattered sunlight achieves greater temporal and spatial coverage since the measurement only requires sunlit conditions. Other techniques have also been successfully used for stratospheric aerosol measurement from space including lidar, stellar occultation and thermal emission, and the combination of various data sets has provided a rich monitoring record of the highly variable aerosol load. However, the current satellite instruments capable of these measurements are operating well past their design lifetimes and very few satellite missions with stratospheric measurement capability are planned. Active discussions are underway in the scientific community about an upcoming gap in stratospheric measurements and the requirements for future measurements of stratospheric aerosol, and in particular the readiness for observations of the next big volcanic eruption (*Kremser et al.*, 2016).

In this thesis work, the design and test flight of a new passive remote sensing instrument, named the Aerosol Limb Imager (ALI), is presented. The long term goal of the work is the eventual realization of the ALI instrument on a small- or micro-satellite platform. ALI is designed to use novel acousto-optic filtering technology to image limb scattered sunlight for the retrieval of high resolution stratospheric aerosol extinction distributions, both vertically and horizontally. The horizontal dimension of the image, when observed from a moving satellite or aircraft platform is often referred to as the cross-track dimension. The hyperspectral approach to the ALI design provides the capability for this cross-track coverage of the limb, which is a feature that to our knowledge has never been performed from an atmospheric composition instrument. This will provide an especially powerful observation set for studying the transport and evolution of often ultra-thin and variable aerosol layers. As part of this work, a prototype of the ALI instrument was developed for proof-of-concept measurements from stratospheric balloon, and a test flight of this prototype occurred from the Canadian Space Agency launch facility in Timmins, Ontario, in 2014. This flight was the first known test of a large-aperature imaging quality acousto-optic filter from a stratospheric balloon, providing important space-flight heritage for the technology.

This thesis presents the motivational background and design of the ALI instrument, the results from the stratospheric balloon test flight, and concludes with a systematic modelling study on the effect of polarization on the aerosol measurement. The work covers a wide range of topics and as such the necessary background material is diverse and multidisciplinary. Chapter 2 outlines the relevant background physics of the atmosphere, with a focus on stratospheric aerosol. This includes its discovery, sources and microphysical properties, and a discussion about the importance of aerosol in the atmosphere including the effect on climate. Following this, an overview of the different techniques used to measure aerosols is presented including both in-situ and remote sensing methods. Particular attention is paid to the limb scattering method, which is the technique used by the ALI instrument. This chapter concludes with a survey of atmospheric radiative transfer and inversion theory, which encompasses the core physics for understanding and interpreting remote sensing observations. This discussion starts with the traditional scalar equations and moves into the more complete polarized, or vector, theory needed for this work. An overview of the comprehensive radiative transfer model developed at the University of Saskatchewan, which is called SASKTRAN (*Bourassa et al*., 2008) and is used extensively within this work, is provided along with a brief survey of standard inverse methods to determine atmospheric parameters from remote sensing measurements.

Chapter 3 begins with an overview of the Acousto-Optic Tunable Filter (AOTF), which is the novel filtering device at the core of the ALI design. The background physics and practical application of this device are covered with a focus on the advantages and disadvantages of using this technology in space-based remote sensing applications. Following this is a detailed discussion of the optical design trade-offs specific to the ALI requirements, and the testing of the chosen optical system design. Chapter 4 details the calibration and performance of the prototype instrument as well as an overview of the control software developed for the stratospheric balloon flight.

Chapter 5 is a presentation of the ALI test flight on a stratospheric balloon in Timmins, Ontario in 2014. The results from the measurements recorded from the flight are presented including calibrated images, retrieved aerosol extinction profiles, a precision estimate, and a retrieval of the particle size distribution from the acquired spectral information. These results are then compared to current coincident satellite measurements.

Finally, the use of the AOTF technology means that ALI inherently measures the linearly polarized radiance, whereas existing satellite instruments that provide the measurement and algorithm heritage are purposefully designed to measure the total radiance with insensitivity to the polarization state. Thus the thesis includes a systematic study, presented in Chapter 6, to determine the full effect of the polarized measurement on the aerosol retrieval capability from simulated satellite-based polarized measurements.