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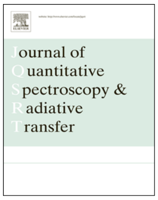

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The sensitivity to polarization in stratospheric aerosol retrievals from limb scattered sunlight measurements

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ABSTRACT

Satellite measurements of limb scattered sunlight at visible and near infrared wavelengths have been used successfully for several years to retrieve the vertical profile of stratospheric aerosol extinction coefficient. The existing satellite measurements are of the total radiance, with very little knowledge or impact of the polarization state of the limb radiance. Recently proposed instrument concepts for stratospheric aerosol profiling have been designed to measure the linearly polarized radiance. Yet, to date, the impact of the polarized measurement on the retrievals has not been systematically studied. Here we use a fully spherical, multiple scattering radiative transfer model to perform a sensitivity study on the effects of the polarized measurement on stratospheric aerosol extinction retrievals through specific investigations of the aerosol signal fraction in polarized measurements, potential retrieval bias, and achievable precision. In this study,we simulate both total and linearly polarized measurements, for a wide range of limb viewing geometries that are encountered in typical low earth orbits and for various aerosol loading scenarios. The orientation of the linear polarization with respect to the horizon is also studied. Taking into account instrument signal to noise levels it is found that in general, the linear polarization can be used as effectively as the total radiance measurement, with consideration of instrument signal to noise capabilities; however the horizontal polarization is more promising in terms of signal magnitude.

1. Introduction

Stratospheric aerosols, which are submicron-sized spherical liquid droplets of sulfuric acid, cause a cooling effect by scattering the incoming solar irradiance and therefore have an important radiative effect on climate. This effect depends strongly on the aerosol concentration, composition, and particle size distribution [1,2]. Recent studies have proposed a link between the so-called global warming hiatus and an increase in the stratospheric sulfate aerosol layer [3–5]. The increase in stratospheric aerosol over the last decade was primarily caused by a series of minor, mostly tropical volcanic eruptions [6] although the impact of anthropogenic pollution sources continues to be studied [7]. As noted in the recent review paper by Kremser et al. [8], there is a distinct need for continued monitoring with global coverage of aerosol, particularly extending down to tropopause altitudes.

Stratospheric aerosol distributions have been monitored on a global scale since the 1970s with satellite instruments using a variety of remote sensing techniques. The first satellite aerosol extinction profile retrievals were from limb sounding solar occultation measurements, most notably from the NASA SAGE missions [9,10]. The solar occultation technique has provided a robust and reliable method to retrieve aerosol extinction by directly measuring the atmospheric transmittance. However, the measuring frequency of occultation measurements is limited due the necessity of a sunrise or sunset and typically requires months to cover a large range of latitudes. Limb scatter measurements, such as from OSIRIS [11], SCIAMACHY [12], and most recently from OMPS [13], have better coverage by only requiring the sunlit conditions at the tangent point, but the retrieval of aerosol is more complex requiring computationally heavy forward modelling and inversion compared to occultation [14–16]. It is worthwhile to note the success of limb scatter aerosol measurements: The combination of the SAGE II and OSIRIS datasets have recently been used to successfully create a single long term merged time series depicting the evolution of the stratospheric aerosol layer [17], and OSIRIS measurements have been used as one of primary extensions of the stratospheric aerosol record for the CMIP6 study [18].

OSIRIS, SCIAMACHY, and OMPS-LP measure the spectral radiance of the scattered sunlight from the limb and use non-linear inversion techniques to retrieve aerosol extinction profiles [13,15,19]. For these retrievals, some assumptions regarding

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particle size distributions and/or composition are always required in the forward model. Most importantly for this study, currently none of these retrievals account for any polarization sensitivity in their respective measurements. However, these instruments have been specifically designed to measure the total radiance by minimizing the instrument sensitivity to polarization. Recently proposed instruments with the capability to measure aerosol using limb scattering include the Belgian instrument Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere (ALTIUS) [20,21] and the Aerosol Limb Imager (ALI), a Canadian endeavour [22]. Both instruments image the limb and use acousto-optic tunable filters to select the measured wavelength. The use of the acousto-optic filter inherently means that the measured image is of the linearly polarized radiance due to the phonon-phonon interaction that selects the filtered wavelength. Although it has been previously shown that the retrieval of stratospheric aerosol extinction profiles from polarized scattered sunlight measurements are possible [22,23], the full impact of the polarized measurement has not been systematically studied. In this work we perform an analysis with simulated polarized measurements to determine first if there are any clear advantages or disadvantages to making the linearly polarized measurement. Further, we investigate which linear polarization and viewing geometries have the largest sensitivities to aerosol, and how the polarized measurements affect the accuracy and precision of the retrieved aerosol product.

2. Background and forward model

In order to investigate the effect of polarization on the sensitivity to aerosol, an accurate model of the polarized limb radiance must be employed. Additionally, a large number of scenarios, including various atmospheric states and viewing geometries, are required to fully probe the solution space. In this section, the basic background describing the polarization state of the limb signal is developed, and the SASKTRAN High Resolution (SASKTRAN-HR) model and the various model scenarios used for the analysis are described. Based on the useful spectral range for limb scatter observations of stratospheric aerosol, we have limited our discussion to wavelengths from 500 to 1500 nm.

2.1. Polarized scattered sunlight and stratospheric aerosols

The time-averaged polarization state of partially polarized, incoherent light can be fully characterized by a Stokes vector,

$$\boldsymbol{I}=\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} \tag{1}$$

where the coefficients of the Stokes vector, defined in a reference frame, are measures of the total radiance, I, the difference between horizontal polarization to vertical polarization, Q, the difference between $+45^\circ$ diagonal polarization to -45° polarization, U, and the difference between the counter clockwise circular polarization to clockwise polarization, V. Scattering events modify the polarization state of scattered light. This modification is described by a scattering matrix, which is valid for Stokes vectors defined in a scattering frame. Using a reference frame where the x-axis is defined to be the horizontal polarization and where x and y axes are orthogonal leads to the following definition for the Stokes parameters

$$\begin{aligned} I &= <E_x>^2 + <E_y>^2 \\ Q &= <E_x>^2 - <E_y>^2 \\ U &= 2\,\mathrm{Re}\left(<E_x><E_y^*>\right) \\ V &= -2\,\mathrm{Im}\left(<E_x><E_y^*>\right). \end{aligned} \tag{2}$$

The polarization state of light propagating along a ray is stored as a Stokes vector defined in some reference frame. When a scattering event is modelled the Stokes vector is rotated into the scattering frame, multiplied by the scattering matrix, and then rotated into a reference frame in which the scattered Stokes vector is stored and is represented by the following operation,

$$\boldsymbol{I}^{sca}= \boldsymbol{L}(\theta_2)\boldsymbol{P}(\Theta)\boldsymbol{L}(\theta_1)\boldsymbol{I}^{inc}. \tag{3}$$

The outgoing, or scattered, and incoming radiances are represented 4 by 1 matrices, i.e. Stokes column vectors, given by $\boldsymbol{I}^{sca}$ and $\boldsymbol{I}^{inc}$, the rotation matrices are denoted $\boldsymbol{L}$ and rotate the incoming ray and scattered ray by rotation angles θ_1 and θ_2. The 4 by 4 scattering matrix is represented by $\boldsymbol{P}(\Theta)$ and is related to the probability that an incoming ray will be scattered at a scattering angle, Θ. It also describes the change in polarization state through the elements of the matrix. The product $\boldsymbol{L}(\theta_2)\boldsymbol{P}(\Theta)\boldsymbol{L}(\theta_1)$ is sometimes referred to as the phase matrix.

For this work, two primary scattering interactions induce and/or modify the polarization state of the light propagating in the atmosphere. These are scattering by the molecular air density and by stratospheric sulfate aerosols. The molecular atmosphere interaction is referred to as Rayleigh scattering, and has a scattering matrix that is determined from the Rayleigh-Gans approximation [24] given by

$$\boldsymbol{P}(\boldsymbol{\Theta})_{\boldsymbol{ray}}=\frac{3}{4}\begin{bmatrix} 1+\cos^2\Theta & -\sin^2\Theta & 0 & 0 \\ -\sin^2\Theta & 1+\cos^2\Theta & 0 & 0 \\ 0 & 0 & 2\cos\Theta & 0 \\ 0 & 0 & 0 & 2\cos\Theta \end{bmatrix} \tag{4}$$

where Θ is the scattering angle.

For randomly orientated or spherical particles, such as stratospheric aerosol, only six elements of the scattering matrix are required [25] which are the following

$$\boldsymbol{P}(\boldsymbol{\Theta})=\begin{bmatrix} P_{11}(\Theta) & P_{12}(\Theta) & 0 & 0 \\ P_{12}(\Theta) & P_{22}(\Theta) & 0 & 0 \\ 0 & 0 & P_{33}(\Theta) & P_{34}(\Theta) \\ 0 & 0 & -P_{34}(\Theta) & P_{44}(\Theta) \end{bmatrix} \tag{5}$$

Additionally, for spherical particles like stratospheric aerosol only four unique terms are required since $P_{11}=P_{22}$ and $P_{33}=P_{44}$. Spherical aerosol scattering at visible and near-infrared wavelengths is fully described by Mie theory [26], for which several standard codes have been developed to calculate scattering cross sections and scattering matrices based on the particle size distribution and index of refraction (e.g. Wiscombe [27]). A full derivation can be found in van de Hulst [25].

The basic polarization state of the scattered light in the Earth's atmosphere can be understood by first considering a single scattering event of the unpolarized incoming sunlight in a molecular atmosphere. For reference, the Solar Scattering Angle (SSA) is defined to be the angle between the direction to the sun and the line of sight. It can be easily seen from the form of the Rayleigh scattering matrix (Eq. (4)) that a single scattering event causes the sky to develop a distinct polarization at a SSA of 90° from the incoming solar beam. Note that the horizontal and vertical polarizations are given by $0.5(I+Q)$ and $0.5(I-Q)$ respectively. The scattered sunlight is linearly polarized in the horizontal orientation, which is parallel to the horizon. The degree of polarization