Sensitivity of stratospheric aerosol retrievals to polarized limb scattered sunlight measurements

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**Abstract: The ability to accurately determine aerosol profiles from a linearly polarized radiance measurement is not well known from a low earth orbit limb scatter geometry. With future instruments measuring linear polarized radiance, such as ALI and ALTIUS, a sensitivity study to determine the effect of polarized measurements on stratospheric aerosol retrievals has been performed. This sensitivity study, including aerosol both retrieval and precision analysis has been performed for simulated measurements of the scalar, horizontal, and vertical polarizations. An analysis of the optimal polarization and geometry for a linear polarized instrument is presented. Both linear polarizations can be successfully used for an aerosol instrument depending on the specific of the orbit and look geometry.**

# **1 Introduction**

Recent studies have proposed a so called global warming hiatus due to an increase in the background stratospheric sulfate aerosol layer. (Solomon et al., 2011; Haywood et al., 2014; Fyfe et al., 2013). The increase in stratospheric aerosol over the last decade is believed to be caused by a series of small-scale tropical volcanos (Hofmann et al., 2009). Stratospheric aerosols cause a cooling effect by scattering incoming irradiance and has an important radiative effect on the climate of the planet which depends on the concentration and particle size distribution (Kiehl and Briegleb, 1993; Stocker et al., 2013).

Aerosols have been monitored on a global scale for decades from instruments on satellites such as the SAGE missions (Russell and McCormick, 1989; Thomason and Taha, 2003), OSIRIS (Llewellyn et al., 2004), SCIAMACHY (Bovensmann et al., 1999), and CALIPSO (Winker et al., 2007). The first satellite aerosol profiles were from limb sounding solar occultation measurements, including the SAGE missions, and have provided a robust and reliable method to retrieve aerosol by directly measuring the optical depth. However, occultation is limited to the number of measurements per day due the necessity of a sunrise or sunset event limiting daily coverage. Limb scatter measurements, such as from OSIRIS and SCIAMACHY, have better coverage by only requiring the sunlit atmosphere but the retrievals of aerosol is computationally heavy compared to occultation. The combination of the datasets have been used to create long merge time series depicting the evolution of the stratospheric aerosol layer (Rieger et al., 2015; Ridley et al., 2014).

OSIRIS, SCIAMACHY, and OMPS measure radiance from the limb and use inversion techniques to determine aerosol profiles (Bourassa et al., 2012b; Ernst et al., 2012, Rault and Loughman, 2013). It should be noted that currently none of these retrievals account for any polarization sensitivity in their respective measurements. Future instruments with the capability to measure aerosol from the limb have been proposed including the Belgium instrument Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere (ALTIUS) (Dekemper et al., 2012) and the Aerosol Limb Imager (ALI), a Canadian endeavour (Elash et al., 2015). Both instruments use acousto-optic tunable filters to select the measured wavelength but can only measure a linear polarized signal, whereas previous limb scatter instruments have used scalar measurements to perform the inversion. It is largely unknown what the effect of measuring polarization will be on limb scatter aerosol retrievals despite the substantial effort already performed on the development of these instruments. In this work we perform an analysis on simulated polarized measurements and determine which linear polarization and geometries have the largest sensitivities to aerosol, and how those polarized measurements affect the accuracy and precision of the retrieved aerosol product. Furthermore, a brief comparison between the scalar and vector models will be performed for verification of the use of the scalar model for scalar retrievals.

# **2 Model and Scenarios and Aerosol Sensitivity**

In order to compare the effect of polarization on the sensitivity to aerosol, one must be able to accurately model polarized radiance. Additionally, a large number of scenarios are required with different atmospheric states and geometries to fully probe the solution space. In this section, the SASKTRAN-HR model used for the analysis with be discussed as well as aerosol scenarios used for the study.

## 2.1 Polarized scattered sunlight and stratospheric aerosols

The polarization for electromagnetic waves can be fully defined by the stokes vector. The stokes vector is given by a column matrix

where the terms of the stokes vector are the total radiance, the horizontal polarization, the +45o diagonal polarization, and the counter clockwise polarization from top to bottom. Using a reference frame where the x-axis is defined to be the horizontal polarization leads to the following definition for the Stokes parameters

To calculate the scattering for an incident ray propagating in a given direction the ray undergoes a rotation into the Stokes reference frame then is multiplied by the phase matrix. After the multiplication the result is rotated back into the ray’s initial coordinate system through the following

The scattered and incoming radiances are 4 by 1 matrices given by and , the rotation matrices are given by and rotates the incoming ray and scattered ray by rotations angles and . The phase matrix is a 4 by 4 represented by . The phase matrix is the effect on how an incoming ray is scattered and into what polarization state.

For the work proposed here two primary scatter interactions induce polarizations in the atmosphere caused by the neutral background and sulfate aerosols. The neutral background atmosphere is composed of nitrogen and oxygen and undergoes Rayleigh scattering. For Rayleigh scattering the phase matrix is determined from the Rayleigh-Gains approximation (Mishchenko et al., 2002) and the phase function is given by

where is the scattering angle.

For random orientated particles only six element of the phase matrix are required (van de Hulst, 1957) which are the following

Additionally, for spherical particles like aerosol only four unique terms are needed since and . Aerosol scattering is modeled by Mie theory (Mie, 1908) which is a complicated and computationally heavy to compute. To fully determine the phase matrix the index of refraction and particle size destitution are required. A full derivation will not be performed here but can be found in van de Hulst (1957).

For the earth’s atmosphere the incoming radiance from the sun is randomly orientated. Once the incoming irradiance enters the earth’s atmosphere the scattered irradiances develops a polarization based on the scattering events. If the atmosphere is question only has Rayleigh scattering and only one scattering event occurs then it gives the sky a distinct polarization at a scatter angle of 90 degrees from the incoming solar beam. The atmosphere is linearly polarized in the horizontal orientation, which is parallel to the horizon and gradually becomes randomly polarized at scatter angles of 0 and 180 degrees. If multiple scattering events are taken into account the degree of polarization is decreased at scattering angle of 90 degrees and does not become completely randomly polarized at full forward and backscatter. Using simulations at 90 degrees scattering the linear polarization is approximately 95%. Furthermore, this polarized effect is strongest at longer wavelengths (1500 nm) and decreases, on average by 10%, as the wavelength become shorter (500 nm). As the scattering angle decreases or increases the linearly polarized aspect of the radiance also decreases down to approximately 20% for a full backscatter of 180 degrees and 30% for a scattering angle of 45 degrees.

If an atmosphere now contains both the scatter from the neutral background as well as sulfate aerosol the effects of Rayleigh and Mie scatter must be accounted for when the sun beam is scattered. If the Rayleigh case previously stated is used as the base case the changes will be noted when aerosol is added. For wavelengths from 500 to 1250 nm a decrease in the horizontal polarization occurs and from 1250 to 1500 nm the opposite occurs. These noted changes are present for all scattering angles. If a background aerosol loading is assumed and the observed change in linear polarization can be as large at 7% but they vary depending on aerosol loading and microphysical parameters.

## 2.2 SASKTRAN-HR model

The radiative transfer model SASKTRAN-HR (High-spatial Resolution) (Bourassa et al., 2007; Zawada et al., 2015) was used for the work in this study. The SASTRAN-HR solves the radiative transfer equation using specified user input for atmospheric species and their concentrations. The SASKTRAN-HR engine uses a fully 3D spherical geometry and it solves the equation using an iterative steps for each order of scatter included in the calculation. A recent addition to SASKTRAN-HR is the ability to calculate fully polarized radiances for the first three scattering events, which contributes to most of the signal in limb scatter (Dueck et al., 2016). The model assumes an incoming unpolarised sun and uses the polarization effects of Rayleigh scattering for neutral atmospheric species and Mie scattering for aerosols to determine the polarization state. Mie scattering has been long used to accurately describe the scattering cross sections and phase functions for aerosol (Mie, 1908) It should be noted that the ground is assumed to be Lambertian and depolarizing.

## 2.3 Aerosol Scenarios

The variety of plausible aerosol profiles within the atmosphere are vast and cannot be completely covered due to the range of particle size distributions and possible concentrations which affect their importance in radiative forcing. Furthermore, with the limb scatter technique, the geometry of the measurement also has a large effect on the sensitivity of the measurement to aerosol due to the sampling of the phase function in the forward model (Rieger et al., 2015). This includes a strong preference for aerosol scattering in the forward direction resulting in a weak signal in the backscatter direction. As well the phase function for aerosol is dependent on the particle size distribution. To probe a large portion of this space, a series of scenarios were derived.

To probe the aerosol space, two profiles and four particle size distributions were used. The two profiles are a background aerosol extinction profile, typical during the volcanically quiet period starting in 1997, and the second profile, which is a representative volcanic profile after the Nabro eruption in 2012 with a higher sulfur injection from the eruption at approximately 20 km. Both profiles can be observed in Figure 1. A multi-modal log-normal particle size distribution was selected with one fine mode and one coarse mode, which can be seen in Table 1. The aerosol profile was chosen to either completely consist of only one of the fine modes or a mix of 50% fine mode and 50% coarse mode. The fine modes are representations of two background aerosol particle size distributions and the coarse mode is a representation of the effect of a volcanic eruption on the size of the aerosol droplets (Deshler et al, 2003). These selected distributions are representations based of off in-situ balloon particle counter measurements from Laramie, Wyoming. For the albedo, values of 0 and 1 were used to set bounds on how ground reflectance affects sensitivity to aerosol with polarized measurements.

To probe the entire geometry, a range of Solar Zenith Angles (SZAs) and Solar Scattering Angles (SSA) were selected. The ranges were selected to give representative selections of all the possible geometries of a limb scatter instrument. The ranges for SZA are 15 o, 45 o, and 75o and for SSA of 30o, 60o, 90o, 120o, 150o, and 180o. And the wavelengths chosen were 500, 750, 1000, 1250, 1500 nm to cover the effect of polarized measurements for wavelengths commonly used by instruments to achieve aerosol profiles from limb instruments (i.e. OSIRIS and SCHIAMACHY aerosol products use the ratio of 750 nm to 470 nm for the aerosol retrieval (Bourassa et al., 2012b; Ernst et al., 2012)) Furthermore, near infrared wavelengths are required to discern particle size information from limb scatter measurements so the 1000-1500 nm wavelength were also selected (Rieger et al., 2014).

## 2.4 Methodology

In order to limit the polarization space of this study, a linear polarized instrument will be assumed that either measures the vertical or horizontal linear polarizations. This was chosen since upcoming instruments like ALTIUS (Dekemper et al. 2012) and ALI (Elash et al., 2015) use an acousto-optic tunable filter for a spectral filter which can only measure linear polarizations. We wanted to be able to answer the question: if only one linear polarization can be observed, which orientation is the best option and how do the polarized measurements compare to the sensitivity of an instrument that measures scalar radiance. The three polarizations used will be defined as the following: linearly polarized radiance aligned with the horizon will be known as the horizontal polarization and linearly polarized radiance that is perpendicular to the horizon will be known as the vertical polarization. The third polarization used is the scalar radiance; it is used as the reference case. Using the Stokes parameters, the scalar radiance is defined as , the horizontal polarization is given by and the vertical polarization is given by .

The study looks at the problem in three sections. How does the fraction of the limb scatter signal that is due to aerosol vary for a range of geometries and aerosol profiles? How does the polarized measurement affect the ability to retrieve aerosol using a consistent assumed particle size distribution? And finally, how does the polarized measurement effect the error on the retrieved profile? Within this section the methodology for each question will be described.

First, the modeled radiance will be compared for a series of geometries, wavelengths, and altitudes to determine the approximate fraction of the signal that is due to aerosol. The model is run with a nominal atmosphere that consists of molecular air, ozone, and NO2 which is kept constant, and with a variable altitude and albedo. The aerosol fraction was determined by calculating the nominal radiance without aerosol in the model, , and the total radiance including the aerosol, , and using the difference between the total radiance and nominal radiance to find the approximate fraction of the signal due to aerosol. Thus to determine the percent of the signal that is attributed, the following formulation is used

Although due to non-linearities from multiple scattering, this is not strictly true; however at most stratospheric tangent altitudes, these wavelengths are quite optically thin and this simple percent difference will provide an intuitive approximation of the fraction of the signal due to aerosol. Furthermore, polarized measurements of radiance will be smaller in magnitude than the scalar counterpart and the percent loss will be used to estimate increases in exposure times needed to compensate.

To determine the effect of polarization on the retrieval, a retrieval method is used similar to aerosol extinction retrieval by Bourassa et al. (2012b). A minor change to the algorithm is made where the measurement vector will not be normalized by a shorter wavelength since work by Rieger et al. (2014) has shown this decreases sensitivity to particle size distributions. Although it is advantageous to limit sensitivity to particle size, future instruments, such as ALI, might not have the ability to measure a shorter reference wavelength and would not be able to use this technique. Furthermore, it is advantageous to know what the worst case scenario would be to know the possible limitations of future technology. For the retrievals, a simulated measurement radiance profile will be calculated using the SASKTRAN-HR model with nominal ozone and NO2 profiles for each of the scenarios listed in section 2.2. The simulated measurements will be used to retrieve aerosol profiles using the Bourassa et al., 2012b technique for all three polarization states. Additionally, a retrieval will be performed with the scalar SASKTRAN-HR model to see if there is a large difference between using the scalar and the polarized model to retrieve aerosol profiles from a scalar measurement. For each aerosol retrieval, the ozone, NO2, and albedo are set the same as in the simulated radiance except the aerosol particle size is fixed as a single mode log-normal with 0.08 µm mode radius and mode width of 1.6. The assumption of a fixed particle size distribution is very common in current limb scatter instruments and will be used to see how the different polarizations are sensitive to particle size distributions and if this incorrect assumption greatly affects the retrieved extinctions for any of the polarizations.

Lastly, an error analysis of the revivals will be performed in order to check the precision of the retrieved aerosol profile. The method used for this analysis is one presented by Bourassa et al. (2012a) in which it is assumed that the Jacobian, , times the Gain matrix, is approximately equal to the identity matrix so

With an assumed covariance on the aerosol retrieval, , the covariance on the aerosol profiles can be found by

Finally, the square root of the diagonal of the aerosol covariance is taken as the final error profile. Using the results from all the cases, statistics will be used to determine trends across the input parameters to find an optimal polarization which the instrument should be orientated to achieve aerosol profiles with the highest precision possible.

# 3 Analysis

## 3.1 Aerosol Sensitivity

The SASKTRAN-HR model was run for many different geometries, both aerosol profiles, and all four particle size distributions. An analysis of the aerosol signal from the different cases will be analysed in this section. The percent of the radiance that is composed of aerosol allows for larger measurement vectors in the retrievals process which generally lead to a higher sensitivity to aerosols during retrievals. Determining the geometries and polarization where the greatest aerosol signal composes the radiance can make future polarized instruments highly sensitive to aerosol.

First, contribution from aerosol was analyzed across wavelength and over a series of altitudes. The aerosol profile demonstrated in Figure 2 is the background aerosol profile with particle size distribution 1 as given in Table 1. Figure 2 demonstrates the percentage of aerosol of one of the linear polarizations minus the percent aerosol of the scalar polarization. The percent aerosol increased as wavelengths become longer. However, the percentage of the signal that is caused by the aerosol has increased in the vertical polarization whereas the horizontal polarization has less sensitivity to aerosol. The aerosol signal generally becomes monotonically stronger as wavelength increases for all polarizations.

A similar analysis was performed using a variety of geometries at a range of altitudes to assess the aerosol signal strength. Figure 3 demonstrates the percent aerosol signal for 15.5 km tangent altitude with the background aerosol loading and an albedo of zero. A sharp difference is noted between the forward and backward scattering geometries. The scalar and horizontal polarization cases follow a similar signal dependence, with the strongest aerosol signal from long wavelengths in the forward scatter direction. For the vertical polarization, we see that it has a strong aerosol signal contribution for all forward scattering directions, even for short wavelengths. For backwards scattering, slightly less aerosol signal is observed, but the shape is similar for aerosol signal from the scalar and horizontal cases. With the vertical polarization, it should be noted that modeling the radiance at a SSA of 90o is very sensitive to particle size distribution due to the low radiance signal, which may make this geometry difficult to perform accurate retrievals. Finally, the SZA only effects the percent of the aerosol signal by less than 0.5% no matter the geometry and is not an important consideration.

The sensitivity of aerosol between horizontal and scalar radiances is approximately the same and the vertical polarization has better sensitivity in the forward scattering case than the backscatter case. However, only measuring a linear polarization results in a loss of overall radiance or signal. In Figure 5, the ratio of the total polarized radiance over the total scalar radiance is shown as a percentage for a SZA of 45o and SSA of 60o with a background aerosol profile. Using a horizontal polarization would result in only observing approximately 58% of the signal for shorter wavelengths compared to the scalar case and at longer wavelengths this increases to approximately 66%. For the back scatter case, the percentage of the lost signal increases slightly to 74% at short wavelength and 80% at long wavelengths. The loss of signal would need to be accounted for by a small increase in exposure times, a mean of approximately 30%. For the vertical polarizations, however the increased aerosol signal in the forward scatter case is met with a loss in overall signal of up to 70% compared to the scalar case and for the backscatter case a decrease of up to 85% is observed. This is a significant loss of signal that will essentially close to double the exposure time. Depending on the expected exposure times for an optical instrument, this may lead to a situation where the increases results in unacceptable times despite the increase in aerosol sensitivity.

Lastly, as the amount of aerosol in the atmosphere increases, so does the percent of the signal which is attributed to aerosol. Eventually, an increase in aerosol will result in little change to the aerosol signal which limits the highest aerosol concentration that can be retrieved from a measurement. In Figure 4, the background aerosol profile is scaled and the percentage of aerosol signal is calculated for each scaled valued with a SZA of 45o and SSA of 60o with an albedo of zero. For all polarizations the rate of increase of aerosol signal increases substantially until approximately 90% of the radiance signal is from aerosol where it slows considerably. At this point it is considered to be saturated which corresponds to a 0.1% increase in aerosol signal for a 0.1 increase of scale factor. For scalar and horizontal cases, saturation first occurs at 25 km when the background aerosol layer is scaled by 9.4. For the vertical polarization, which had higher sensitivity to aerosol in the forward scatter geometry, we see a cap of aerosol sensitivity at 4.4 times the background aerosol layer. For large volcanic eruptions this would limit the aerosol concentration profiles that could be retrieved from limb scatter instrument.

The vertical polarization yields significantly more aerosol signal in the forward scattering case when compared to the horizontal polarization. However, this increase in aerosol signal would result in exposure times that would be 70-85% longer than the horizontal polarization and would not be as effective as measuring aerosol during large volcanic eruptions.

## 3.2 Retrievals

Retrievals were performed for all of the wavelengths listed in section 2.2, however due to similarities between the retrievals of different wavelengths only the 750 nm wavelength will be focused on with comments on the other wavelengths necessary when deviations from the 750 nm case occur.

Retrievals with current limb scatter instruments use a scalar radiative transfer model but accounting for the vector component alters the overall scalar radiance. A quick study was performed to determine if using a scalar model for these retrievals instead of a vector model would result in large changes in the aerosol profiles. For the unpolarised case, the aerosol retrieval was performed with both the scalar and vector SASKTRAN-HR model. A comparison between the retrieved extinctions for the scalar and vector model were performed using a percentage difference in the form

Across all wavelengths, the mean percent difference is less than 2% from 15 to 37 km. However, at shorter wavelengths, for example 750 nm shown in Figure 6, a few outliers occur where the difference between the retrievals is greater than 7%. All of these retrievals occur in the backscatter condition where the SSA is greater than 90o. The reason for this discrepancy is not known at shorter wavelengths, and may be due to changes in the scalar radiance due to polarization interactions but further investigation is required. However, overall the agreement between the retrievals using the scalar and vector models are minuscule and any form of discrepancy vanished for wavelengths past 1000 nm. Since the use of the vector model can increase calculation times by a factor of two for the retrievals, it is beneficial to be able to use the scalar model for scalar radiance retrievals and can be performed for most cases.

Aerosol profiles were retrieved using an assumed particle size distribution, in this case a log-normal with a mode radius and width of 0.08 µm and 1.6 respectively, which was different than the true state. For the three tested polarization states, aerosol profiles were retrieved and separated by particle size distributions and compared against the true extinction state. The 750 nm aerosol comparisons separated by polarizations states and particle size distributions can be seen in Figure 7. It should be noted that geometries with SSA of 90o have been removed for the vertical polarization due to the weak phase function that is strongly dependant on the particle size distribution. This results in a large bias in the retrieved aerosol profile. However, using a geometry with a SSA of 85o or 95o almost eliminates the bias seen at the 90o scattering angle and it is completely eliminated once the scattering angle is less than 80o or greater than 100o.

Now each of the distributions will be examined to notice any offsets from the true aerosol state. For particle size distribution one (see Table 1), retrieved aerosol extinction profiles are too large. For scalar, horizontal, and vertical polarizations had mean offsets of -9-13%, -12-17%, and -6-8% respectively from 17 to 35 km. Particle size distribution two shows a different mean offset, larger, and a higher variance is observed. The mean offset for distribution two are -20-28%, -24-31%, and -12-16% for the same polarizations from 17 to 35 km. For distributions three and four, similar variances are noted between the similar fine modes but the aerosol extinction retrieved is now much smaller than that true extinction state for all three polarizations. For distributions three and four, the mean offsets were 42-44%, 40-43%, and 45-46% and 26-33%, 22-29%, and 38-42% respectively for the same polarization ordering. Furthermore, as wavelength increases an approximately 3-5% increase in offset is observed for the retrieved aerosol profiles for each polarization. Current satellite instruments only agree to each other within 20-30% and using the above trends, accurate aerosol retrievals could be obtained for atmospheric states where only a fine mode exists. However, when a coarse mode is present in the true state, the retrieval significantly underestimates the amount of aerosol in the atmosphere. It should be noted that horizontal polarization retrieves slightly higher extinction values compared to the vertical polarization, on average 8.5% higher. Resulting in a horizontal retrieval that is closer to the true state but still too small by 20-40%. Volcanic eruptions are the main cause for a perturbation in the size distribution and this would lead to an underestimation of aerosol extinction after a significant eruption which can miss a noticeable climate forcing effect.

## 3.3 Precision analysis

Using SASKTRAN-HR, the Jacobians for all the retrieved aerosol profiles were calculated, which were then inverted to determine the gain matrix which were used in Eq. 8 to determine the precision. It should be noted that not all of the Jacobians were stable enough to be inverted due to the lower altitudes being saturated with aerosol and an increase in the measurement vectors did not cause a change in the retrieved aerosol. This caused these cases to be removed from the data set. Unfortunately, this resulted in a large portion of the SSA 30o cases not to invert properly and left too few for accurate statistics and were removed. Overall, these led to a loss of 9% of all of the retrieved scans for the precision analysis.

A value of 1% was chosen for error in the measurement vector which is similar to errors seen from the OSIRIS instrument. The same error was selected no matter the polarization or geometry which would allow the determination of the absolute effects of precision possible by an instrument with the same noise no matter the polarization measured. The diagonal of the covariance matrix, , was 0.2% since it consisted of the altitude measured and the error in the reference altitude. The cross terms of the covariance matrix was 0.1% to represent the error in the normalization altitude. For each parameter listed in section 2.2 the data was separated and a percent error of the retrieved radiance was determined. The percent error was used to determine the standard deviation and mean for each polarization and parameter. With the statistics trends were determined for each polarization and parameter to determine if there was a large effect on the overall precision depending on the test parameters. However, the 500 nm wavelength resulted in precision estimates that were large and noisy. This lead to forming a bias in the results for the tested input parameters and was removed when doing the analysis. The remaining profiles were used to determine the percent error at each altitude and each linear polarization was compared to the scalar base case. The analysis was performed for the SSA, SZA, albedo, extinction type, fine mode type, percentage of coarse mode, and wavelength.

After completing the analysis two primary results were noted. First, the vertical polarization shows a relative percent error improvement of on average 5-10% for forwarding scattering cases across altitudes from 15 to 29 km that decreases as altitude increases. For backscatter scattering cases the linear polarizations yield the same percent error as the scalar case with a maximum relative percent difference of 2%. The other major note is the change of relative error with wavelength. At 750 nm the vertical polarization sees a 15% relative improvement over the base case at 16 km and gradually increase to a 20% improvement at 28 km. For 1000 and 1250 nm the vertical polarizations and scalar once again have very similar present errors and at 1500 nm about a 5% worse relative error is seen at the lower altitudes but reaches par with the scalar case at approximately 20 km. For the horizontal case the same magnitude but opposite effects occurs for the precision. The other parameters tested (i.e. albedo, SZA, etc.) do not show a significance difference between the different polarizations and do not appear to have a large effect on the precision of the profiles.

At most a 3-4% difference in errors were noted between different polarizations for the same test parameters, such as SSA and albedo. As such the choice of polarization does not significantly affect the precision of the aerosol extinction profile assuming same precision on the measurement vector. For the best possible precision in terms of geometry an instrument should be primarily orientated to capture forward scatter signal (SSA less than 90o) at longer wavelengths into the NIR. In the trend analysis as the SSA increases a significant increase of the percent error was noted by approximately double or triple depending on the altitude. Similarly a strong decrease in the percent error was noted as the wavelength increased, once again a decrease of double to triple depending on the altitude.

As a final note the sensitivities of aerosol signal noted in section 3.1 was not accounted for in this analysis which in reality would alter the precision for an identical instrument measuring opposite polarizations. If we assume the instrument is calibrated such that the exposure time is set to measure the same quantity of radiance no matter the polarization then it can be determined how this would affect the precision estimate. Since the error in the measurement vector is dependent on the aerosol signal a smaller contribution of signal from aerosol would result in a larger uncertainty in the retrieved profile. This would result in the highest precision measurements from a vertically polarized instrument since the increase in aerosol signal is larger than the horizontal polarization. The precision increase would be at most a couple of percent better than the horizontally polarized case. However, if it is assumed that a constant exposure time is selected no matter the polarization, the increase in overall radiance from the horizontal polarization would result in a higher precision measurement compared to the vertical case. However, in this scenario the horizontal polarization would have a percent error on the aerosol profile of approximately half compared to the vertical polarization which would vary depending on the aerosol extinction profile and the viewing geometry.

# **4. Conclusions**

Overall choice for a polarized instrument that can only measure one polarization focused at retrieving high quality aerosol products is not a simple answer and depends on several parameters. The overall best situation would be an instrument that measures forward scattered light with vertical polarization with compensated exposure times. Recall that the vertical polarization is defined as the polarization normal to the horizon. In this orientation, the radiance measurement has good sensitivity to aerosol across all altitudes greater than 13 km. However, the increased sensitivity, especially at the shorter wavelengths, falls off quite rapidly once a SSA of 90o is surpassed. This instrument would also yield the best precision possible but it has two disadvantages. First, assuming a particle size distribution scattering angles close to 90o contain a bias in the retrieved aerosol extinction. Second, a large loss of the overall signal occurs from measuring the vertical polarization, up to 70% for forward scatter which would increase exposure times or if not accounted for decrease precision. Depending on instrument specifications, the required increase in exposure time may result in unacceptably high values.

If more signal is required or the orbit will result in a high percent of measures around a SSA of 90o, the horizontal polarization should be used. However, the preference would be for forward scatter at the longer wavelengths since a loss of aerosol signal occurs at shorter wavelengths. This would result in the highest possible aerosol signal in the radiance. Furthermore, a maximum of loss of signal would only be 42% for forward scatter which is considerably better than the vertical polarized case.

As a final note, the agreement between the scalar and vector SASKTRAN-HR model are generally within 2% of each other for the aerosol retrievals. It is promising that the inclusion of polarization in the model does not cause a large change to the retrieved profiles since the use of the vector model would result in an approximate doubling in processing time.

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# References

Bourassa, A. E., D. A. Degenstein, R. L. Gattinger, and E. J. Llewellyn (2007), Stratospheric aerosol retrieval with optical spectrograph and infrared imaging system limb scatter measurements, Journal of Geophysical Research, 112, D10217, doi:10.1029/2006JD008079.

Bourassa, A. E., C. A. McLinden, A. F. Bathgate, B. J. Elash, and D. A. Degenstein (2012a), Precision estimate for Odin-OSIRIS limb scatter retrievals, Journal of Geophysical Research: Atmospheres, 117, D04303, doi:10.1029/2011JD016976.

Bourassa, A. E., L. A. Rieger, N. D. Lloyd, and D. A. Degenstein (2012b), Odin-OSIRIS stratospheric aerosol data product and SAGE III intercomparison, Atmospheric Chemistry & Physics, 12, 605-614, doi:10.5194/acp-12-605-2012.

Bovensmann, H., J. Burrows, M. Buchwitz, J. Frerick, S. Noël, V. Rozanov, K. Chance, and A. Goede (1999), SCIAMACHY: Mission objectives and measurement modes, Journal of the Atmospheric Sciences, 56, 127-150.

Dekemper, E., N. Loodts, B. V. Opstal, J. Maes, F. Vanhellemont, N. Mateshvili, G. Franssens, D. Pieroux, C. Bingen, C. Robert, L. D. Vos, L. Aballea, and D. Fussen (2012), Tunable acousto-optic spectral imager for atmospheric composition measurements in the visible spectral domain, Applied Optics, 51, 6259-6267, doi:10.1364/AO.51.006259.

Dueck, S., A. E., Bourassa, and D. A. Degenstein (2015), SASKTRAN-HR Polarization Module, In Preparations.

Deshler, T., M. Hervig, D. Hofmann, J. Rosen, and J. Liley (2003), Thirty years of in situ stratospheric aerosol size distribution measurements from Laramie, Wyoming (41 N), using balloon-borne instruments, Journal of Geophysical Research: Atmospheres (1984-2012), 108.

Elash, B. J., A. E. Bourassa, P. R. Loewen, N. D. Lloyd, and D. A. Degenstein (2015), The Aerosol Limb Imager: Acousto-Optic Imaging of Limb Scattered Sunlight for Stratospheric Aerosol Profiling, Atmospheric Measurements and Techniques, In Procedings

Ernst, F., C. von Savigny, A. Rozanov, V. Rozanov, K.-U. Eichmann, L. A. Brinkho, H. Bovensmann, and J. P. Burrows (2012), Global stratospheric aerosol extinction profile retrievals from SCIAMACHY limb-scatter observations, Atmos. Meas. Tech., 5, 5993-6035, doi:10.5194/amtd-5-5993-2012.

Fyfe, J. C., N. P. Gillett, and F. W. Zwiers (2013), Overestimated global warming over the past 20 years, Nature Climate Change, 3, 767-769.

Haywood, J. M., A. Jones, and G. S. Jones (2014), The impact of volcanic eruptions in the period 2000-2013 on global mean temperature trends evaluated in the HadGEM2-ES climate model, Atmospheric Science Letters, 15, 92-96, doi:10.1002/asl2.471.

Hofmann, D., J. Barnes, M. O'Neill, M. Trudeau, and R. Neely (2009), Increase in background stratospheric aerosol observed with lidar at Mauna Loa observatory and Boulder, Colorado, Geophysical Research Letters, 36, doi:10.1029/2009GL039008, l15808.

Kiehl, J. T., and B. P. Briegleb (1993), The relative roles of sulfate aerosols and greenhouse gases in climate forcing, Science, 260, 311-314, doi:10.1126/science.260.5106.311.

Llewellyn, E., N. D. Lloyd, D. A. Degenstein, R. L. Gattinger, S. V. Petelina, A. E. Bourassa,J. T. Wiensz, E. V. Ivanov, I. C. McDade, B. H. Solheim, J. C. McConnell, C. S. Haley,C. von Savigny, C. E. Sioris, C. A. McLinden, E. Grifoen, J. Kaminski, W. F. J. Evans, E. Puckrin, K. Strong, V. Wehrle, R. H. Hum, D. J. W. Kendall, J. Matsushita, D. P. Murtagh, S. Brohede, J. Stegman, G. Witt, G. Barnes, W. F. Payne, L. Piche, K. Smith, G. Warshaw, D. L. Deslauniers, P. Marchand, E. H. Richardson, R. A. King, I. Wevers, W. McCreath, E. Kyrola, L. Oikarinen, G. W. Leppelmeier, H. Auvinen, G. Megie, A. Hauchecorne, F. Lefevre, J. de La Noe, P. Ricaud, U. Frisk, F. Sjoberg, F. von Scheele, and L. Nordh (2004), The OSIRIS instrument on the Odin spacecraft, Canadian Journal of Physics, 82, 411-422, doi:10.1139/p04-005.

Mie, G. (1908), Considerations on the optics of turbid media, especially colloidal metal solutions, Ann. Phys. (Leipzig)., 42, 377.

Mishchenko, M. I., L. D. Travis, and A. A. Lacis (2002), Scattering, Absorption, and Emission of Light by Small Particles, 3rd edition, Cambridge, UK: Cambridge University Press.

Rault, D. F., and R. P. Loughman (2013), The OMPS limb profiler environmental data record algorithm theoretical basis document and expected performance, Geoscience and Remote Sensing, IEEE Transactions on, 51, 2505-2527.

Ridley, D. A., S. Solomon, J. E. Barnes, V. D. Burlakov, T. Deshler, S. I. Dolgii, A. B. Herber, T. Nagai, R. R. Neely, A. V. Nevzorov, C. Ritter, T. Sakai, B. D. Santer, M. Sato, A. Schmidt, O. Uchino, and J. P. Vernier (2014), Total volcanic stratospheric aerosol optical depths and implications for global climate change, Geophysical Research Letters, 41, 7763-7769, doi:10.1002/2014GL061541, 2014GL061541.

Rieger, L. A., A. E. Bourassa, and D. A. Degenstein (2014), Stratospheric aerosol particle size information in Odin-OSIRIS limb scatter spectra, Atmospheric Measurement Techniques, 7, 507-522, doi:10.5194/amt-7-507-2014.

Rieger, L. A., A. E. Bourassa, and D. A. Degenstein (2015), Merging the OSIRIS and SAGE II stratospheric aerosol records, Journal of Geophysical Research: Atmospheres, doi:10.1002/2015JD023133, 2015JD023133.

Russell, P., and M. McCormick (1989), SAGE II aerosol data validation and initial data use: An introduction and overview, Journal of Geophysical Research: Atmospheres (1984-2012), 94, 8335-8338.

Solomon, S., J. S. Daniel, R. R. Neely, J.-P. Vernier, E. G. Dutton, and L. W. Thomason (2011), The persistently variable background stratospheric aerosol layer and global climate change, Science, 333, 866-870, doi:10.1126/science.1206027.

Stocker, T. F., D. Qin, G.-K. Plattner, M. M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley (2013), Climate Change 2013 The Physical Science Basis.

Thomason, L. W., and G. Taha (2003), SAGE III aerosol extinction measurements: Initial results, Geophysical research letters, 30.

Winker, D. M., W. H. Hunt, and M. J. McGill (2007), Initial performance assessment of CALIOP, Geophysical Research Letters, 34.

Zawada, D. J., S. R. Dueck, L. A. Rieger, A. E. Bourassa, N. D. Lloyd, and D. A. Degenstein (2015), High resolution and Monte Carlo additions to the SASKTRAN radiative transfer model, Atmospheric Measurement Techniques, 8, 3357-3397, doi:10.5194/amtd-8-3357-2015.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Particle size distributions | Fine mode radius (µm) | Fine mode width | Coarse mode radius (µm) | Coarse mode width | Percent extinction coarse mode (%) |
| 1 | 0.04 | 1.8 | -- | -- | 0 |
| 2 | 0.12 | 1.25 | -- | -- | 0 |
| 3 | 0.04 | 1.8 | 0.30 | 1.15 | 50 |
| 4 | 0.12 | 1.25 | 0.30 | 1.15 | 50 |

Table 1: Different particle size distributions used to test the sensitivity of the aerosol retrieval.



Figure 1: 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.

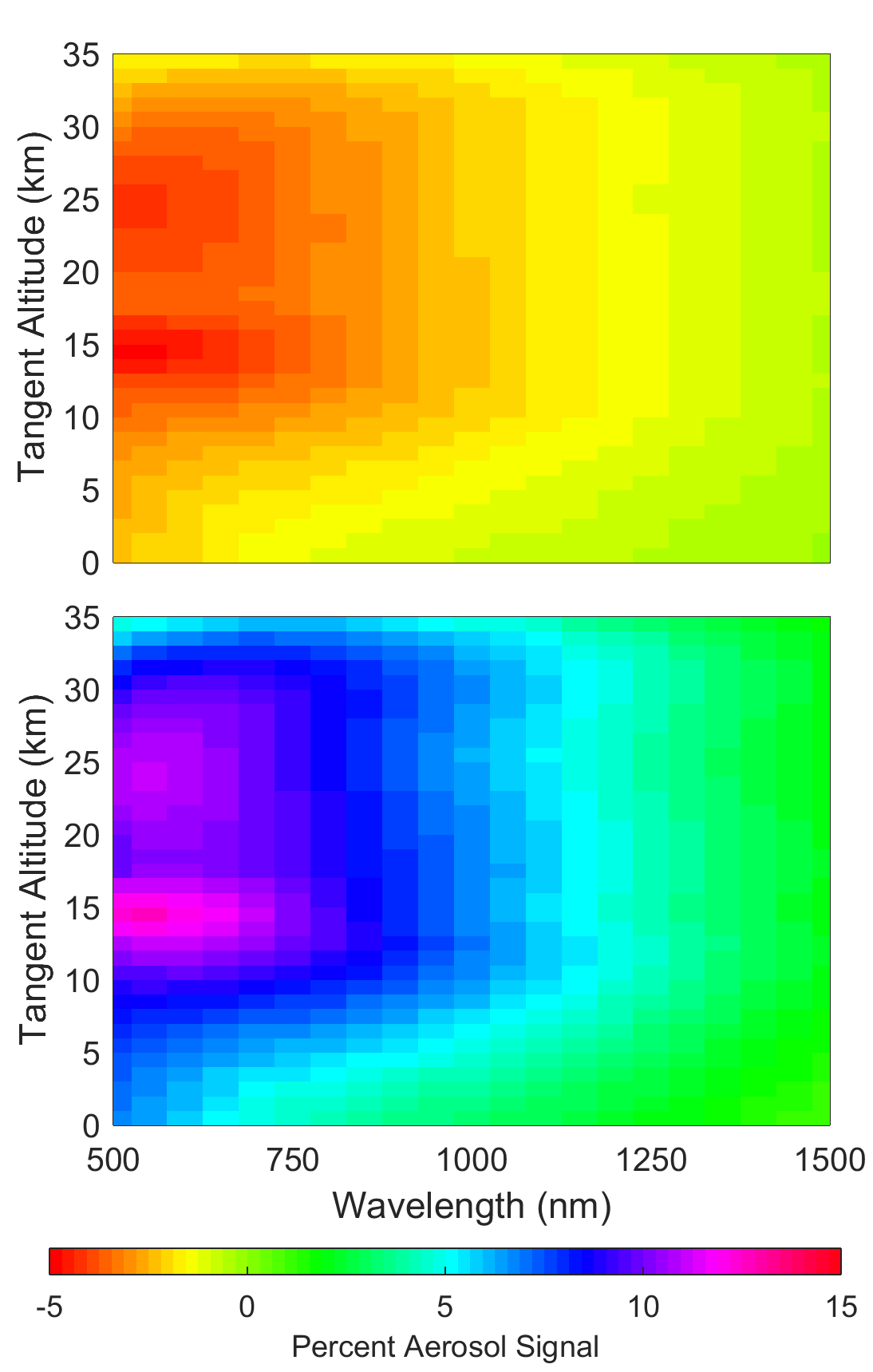


Figure 2: A computation of the percentage of aerosol signal change in the horizontal and vertical polarizations compared to the scalar. The top, middle, and bottom figures are the unpolarised, horizontal, and vertical polarization respectively. The geometry for the simulation is set up with SZA of 45o and SSA of 60o with an Albedo of 0 and using the background aerosol profile.

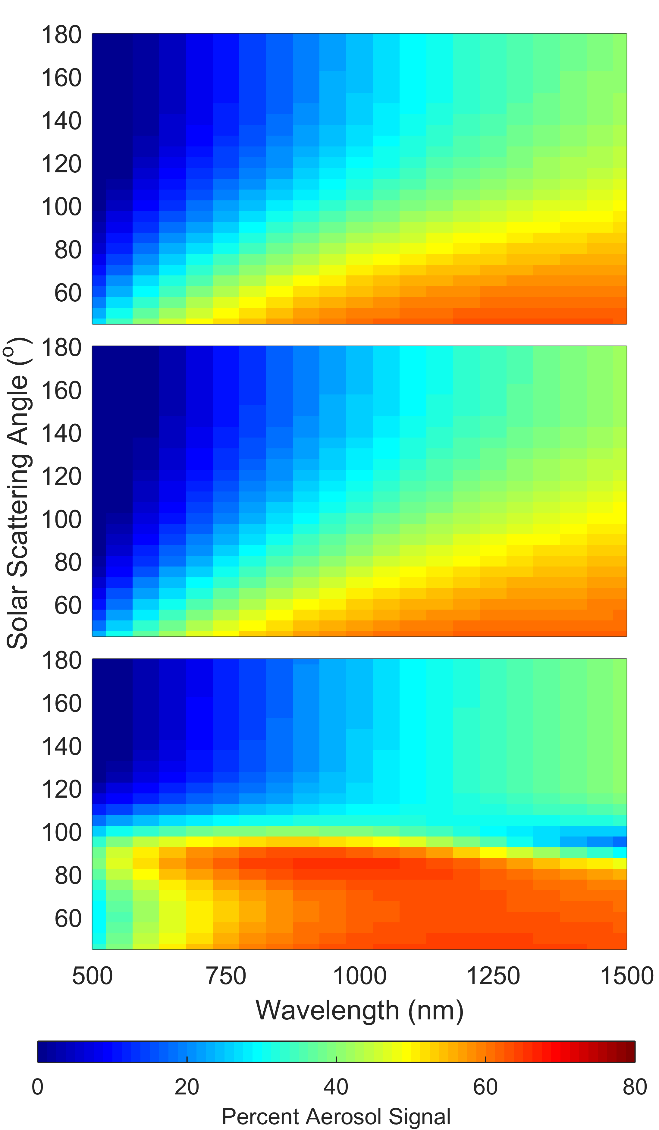


Figure 3: A computation of the percentage of aerosol signal over the total radiance for a three polarizations. The top, middle, and bottom figures are the unpolarised, horizontal, and vertical polarization respectively. The geometry for the simulation is set up with SZA of 45o and at an altitude 15.5 km with an Albedo of 0 and using the background aerosol profile.

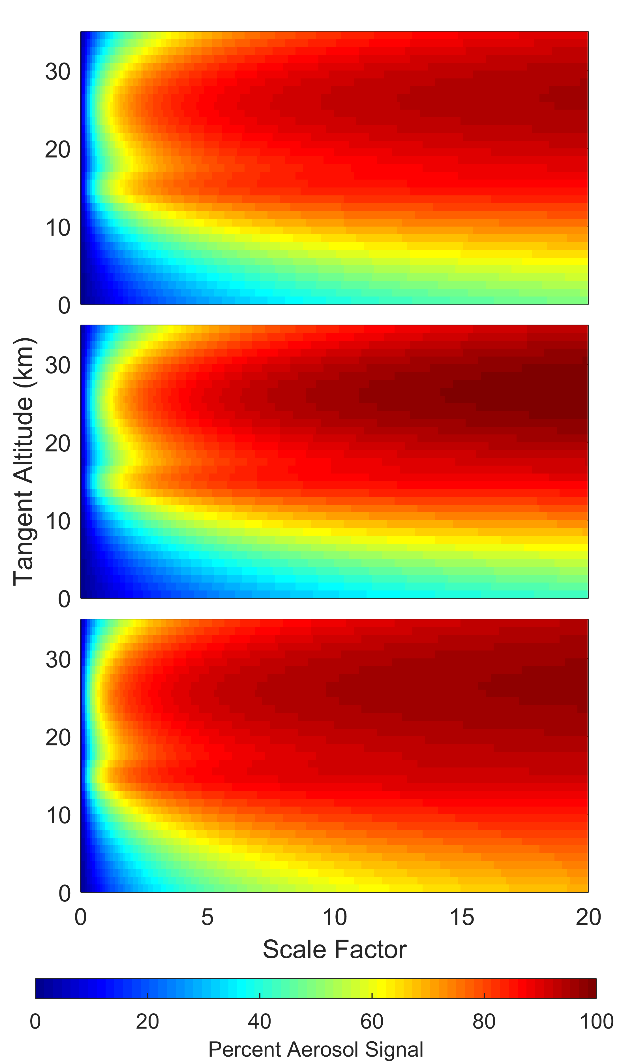


Figure 4: Similar to Figure 2 except only 750 nm wavelength is observed and the aerosol concentration has been scaled to determine where the signal saturated with aerosol.

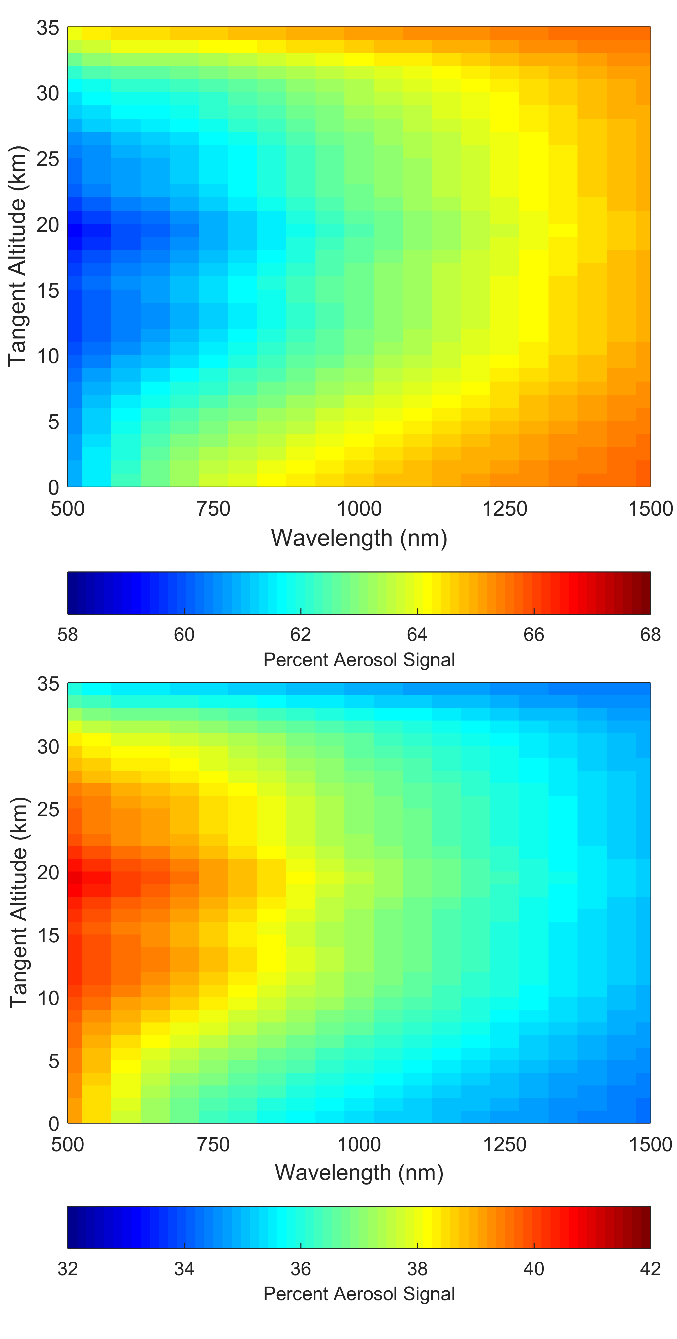


Figure 5: A percent of the linear polarized radiances over the scalar radiance, the top and bottom figures are the horizontal and vertical polarizations respectively. The radiances were calculated with a geometry of 60o SZA and 45o SSA with an albedo of 0 and using the background aerosol profile. Note that the scale for each plot are different.



Figure 6: Percent differences of the retrieved aerosol profiles for the scalar retrieval versus the vector retrieval. Each column represents a different particle size distribution and the labels can be cross referenced in Table 1.

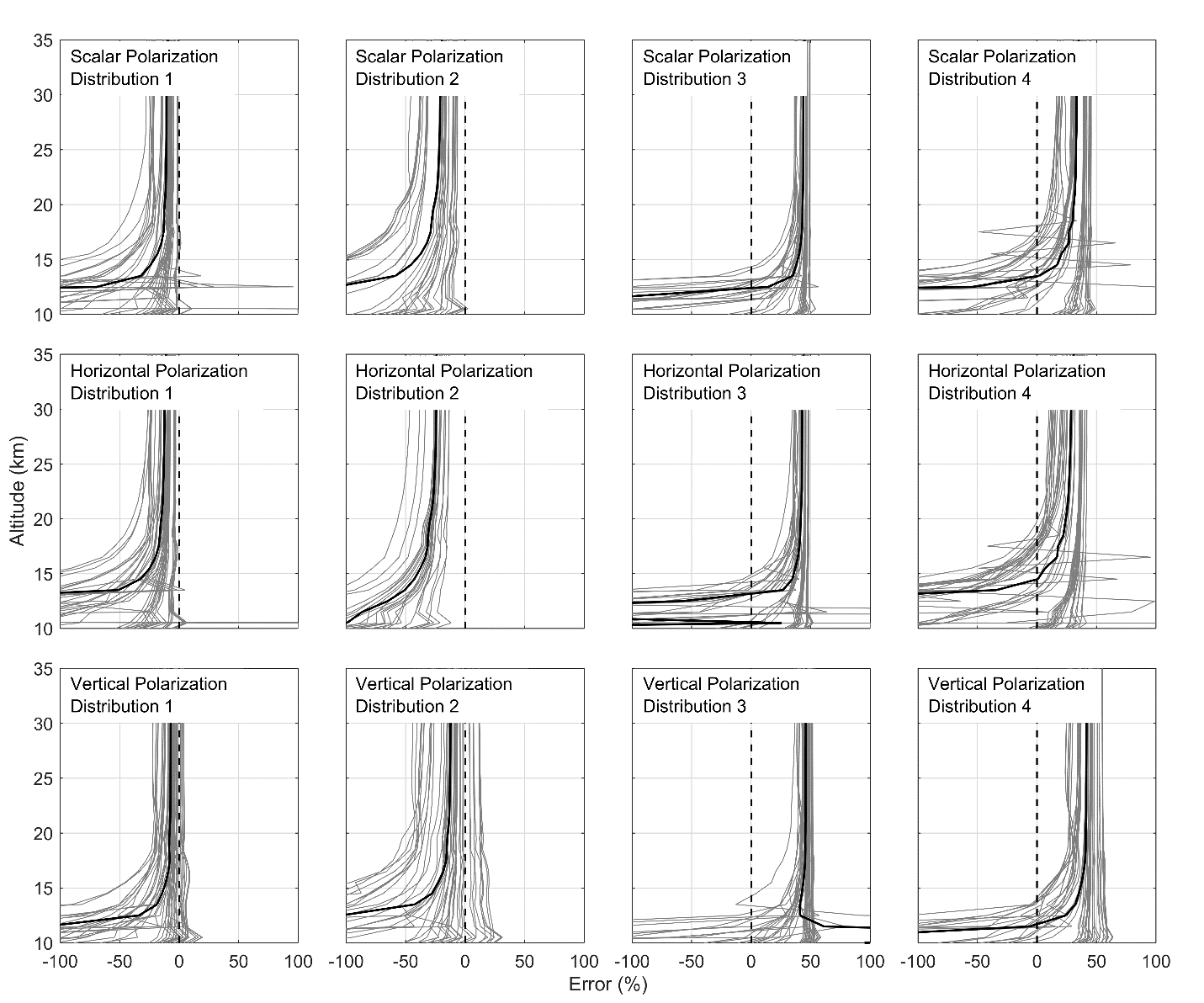


Figure 7: The retrieved aerosol profiles for each unique combination of geometry and aerosol profile are compared again the known original sates. The plot are separated into 12 cases. The four columns represent the four particle size distributions used for the analysis as listed in Table 1. From the top to bottom row are the unpolarised, horizontal, and the vertical polarization.