CHAPTER 4

AEROSOL SENSITIVITY TO POLARIZATION

# 4.1 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 ALTIUS (*Dekemper et al.*, 2012) and ALI, a Canadian endeavor developed in this work. 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. This work will 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.

# 4.2 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.

## 4.2.1 Model

The model used for this work is the SASKTRAN-HR radiative transfer model discussed in section 2.4.5. For the work used here both the scalar and vector modes were used, however the vector mode was primarily utilized. The scalar model was used for scalar retrievals to compare the results to the vector counterpart.

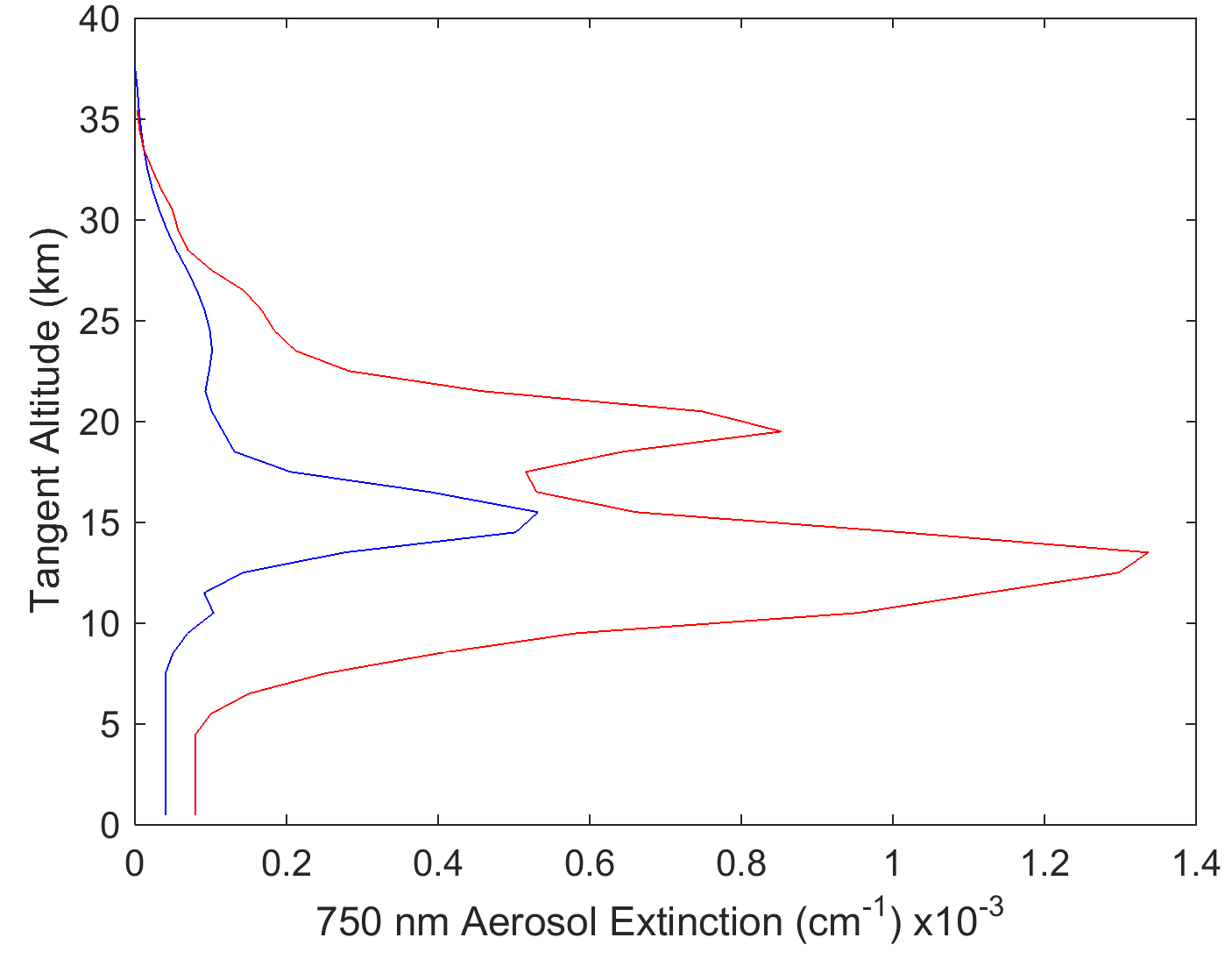
## 4.2.2 Aerosol Scenarios

The variety of plausible aerosol profiles within the atmosphere are vast and cannot be completely covered due to the vast 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 can have 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.

**Table 4-1:** Different particle size distributions used to test the sensitivity of the aerosol retrieval.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| 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 |

To probe the aerosol space, two profiles and four particle size distributions were used. The two profiles are a background aerosol extinction profile, typical used 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 4-1. A log-normal particle size distribution was selected with one fine mode and one coarse mode, which can be seen in Table 4-1. The aerosol profile could either completely consist of only one of the fine mode 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, a value of 0 and 1 were used to determine how ground reflectance effects aerosol sensitivity on polarization measurements.



**Figure 4-1:** 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.

To probe the entire geometry, a range of SZAs and SSAs 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 15o, 45o, 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 used 750 nm (*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 chosen (*Rieger et al.*, 2014).

## 4.2.3 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 use an AOTF for a spectral filter which can only measure linear polarizations. So if only one linear polarization must be used to retrieve aerosol, which is the best option and how do the polarized measurements compare to the sensitivity of an instrument that measures scalar radiance. The three polarizations selected will be define as the following: radiance that aligned with the horizon will be known as the horizontal polarization and radiance that is perpendicular to the horizon will be known as the vertical polarization. The third polarization used the total radiance which will be known as 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

|  |  |
| --- | --- |
|  | (4.1) |

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 assess 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 4.2.2. 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

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|  | (4.2) |

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

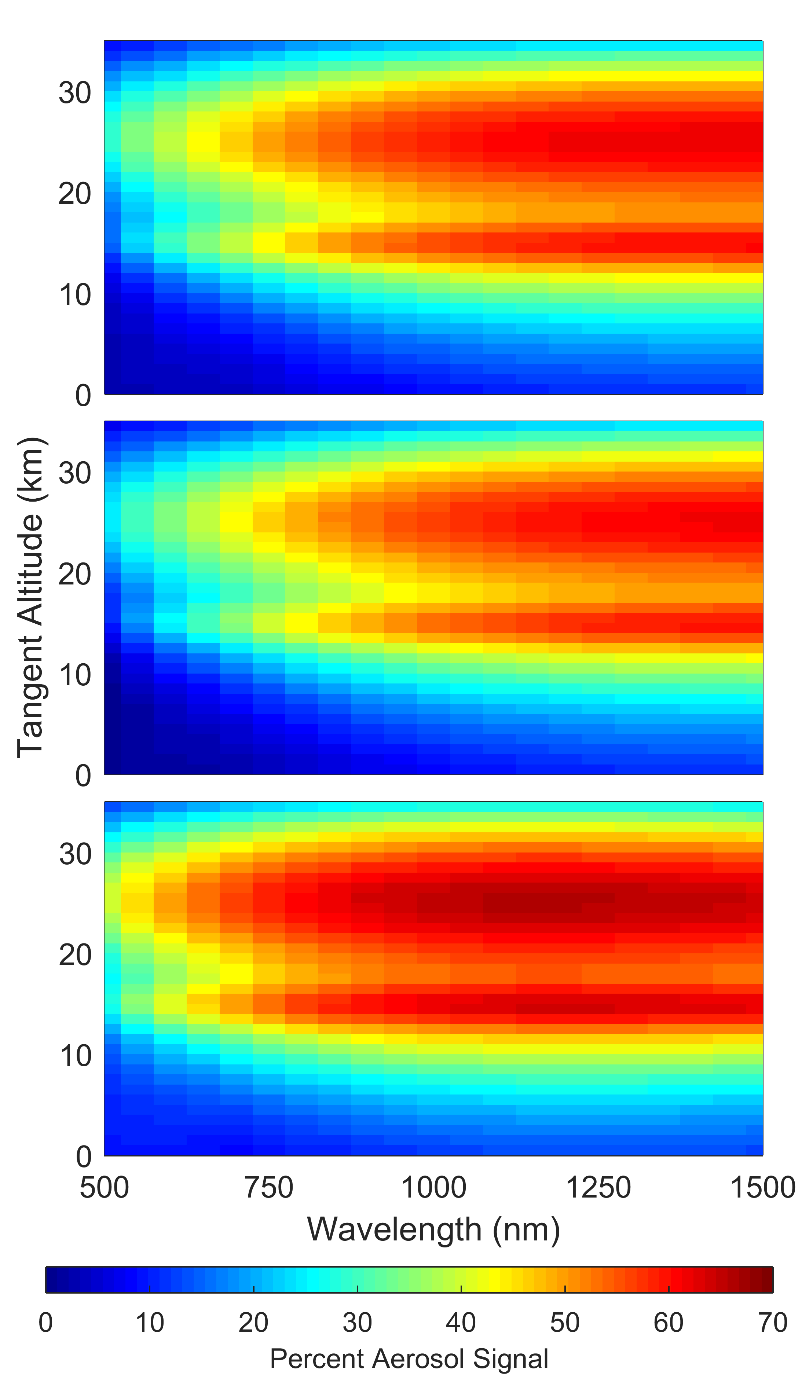
|  |  |
| --- | --- |
|  | (4.3) |

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.

# 4.3 Analysis

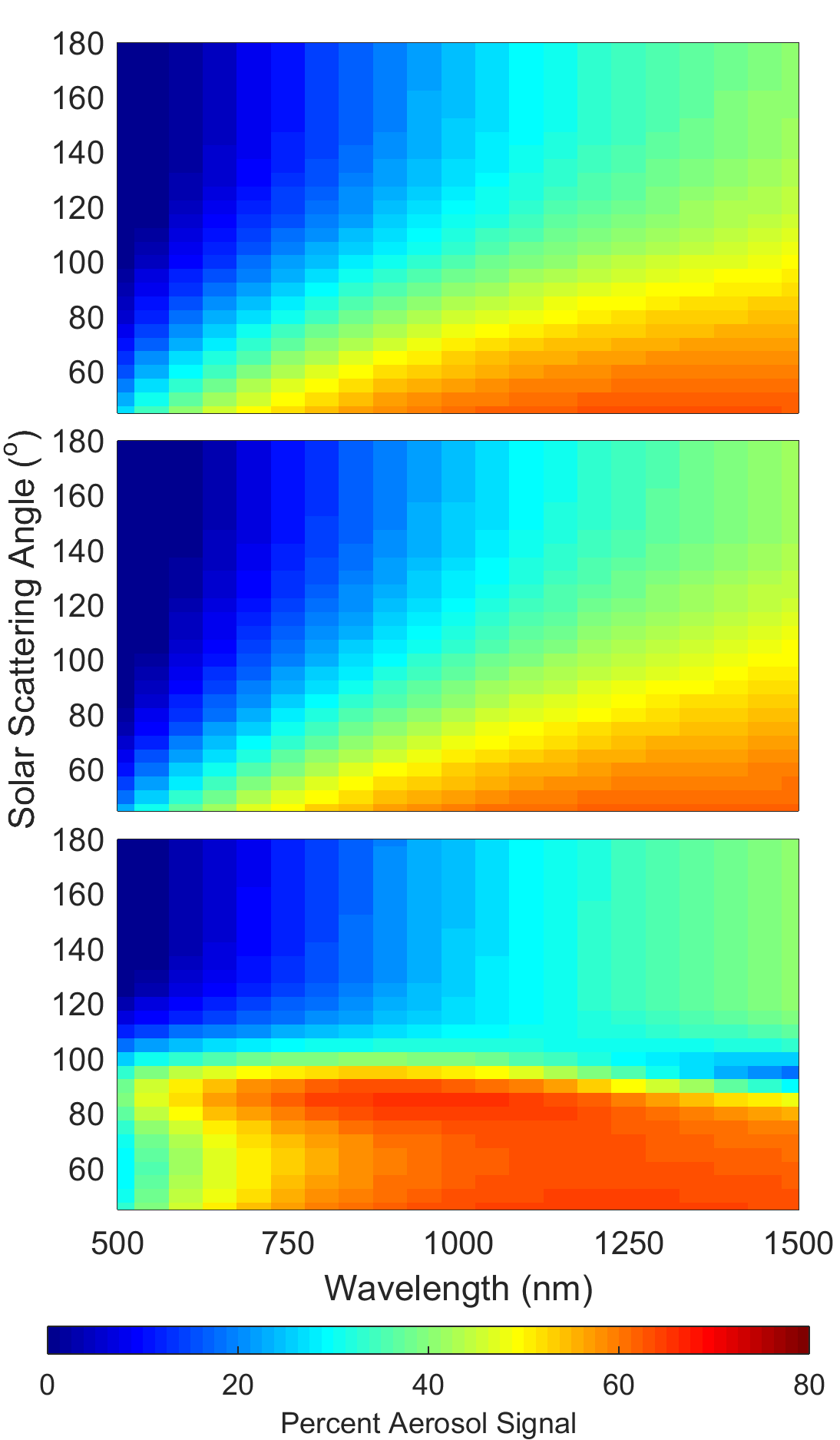
## 4.3.1 Aerosol Sensitivity

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 analyzed 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.



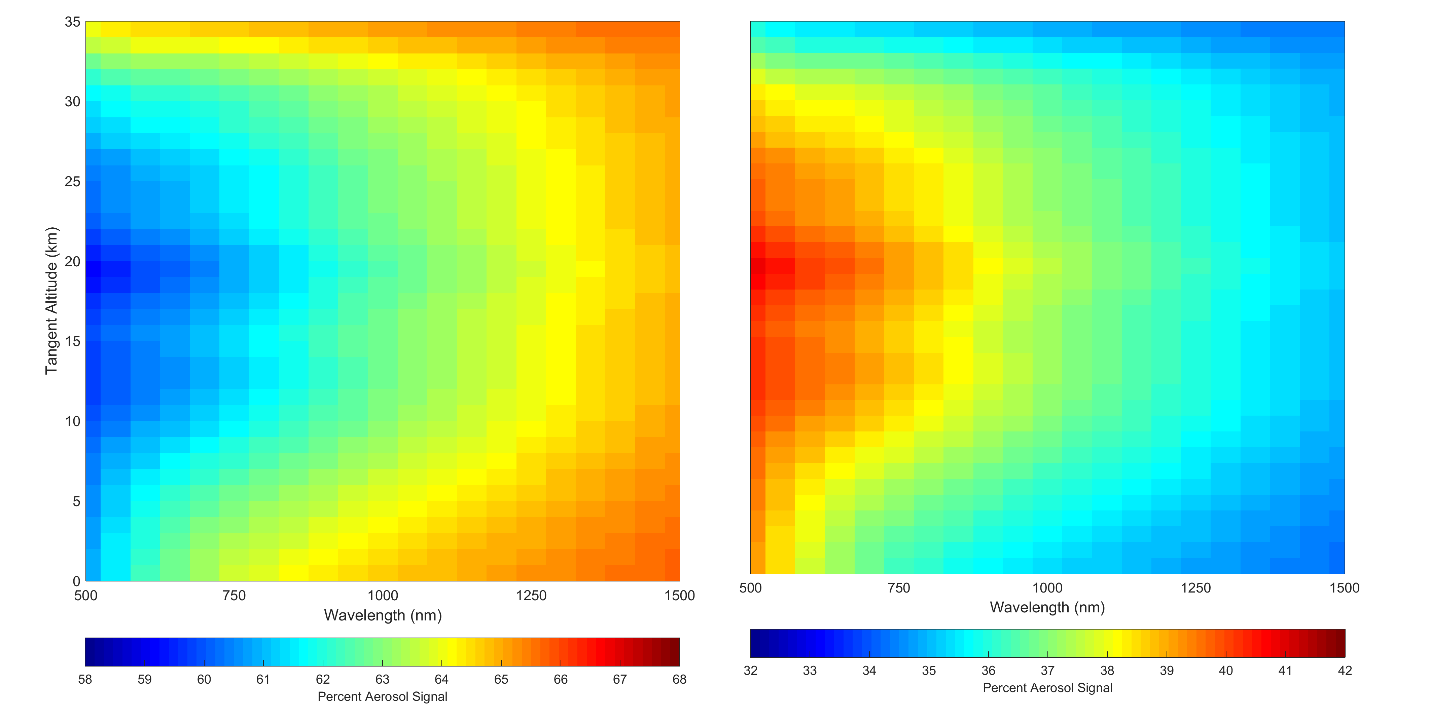
**Figure 4-2:** A computation of the percentage of aerosol signal over the total radiance for a three polarizations. The top, middle, and bottom figures are the unpolarised, horizontal, and vertical polarization respectively. The geometry for the simulation is set up with SZA of 45o and SSA of 60o with an Albedo of 0 and using the background aerosol profile.

First, contribution from aerosol was analyzed across wavelength and over a series of altitudes. The aerosol profile demonstrated in Figure 4-2 is the background aerosol profile with particle size distribution 1 as given in Table 4-1. Figure 4-2 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.



**Figure 4-3:** Similar to Figure 4-2 except the 15.5 km altitude is selected across a range of SSA.

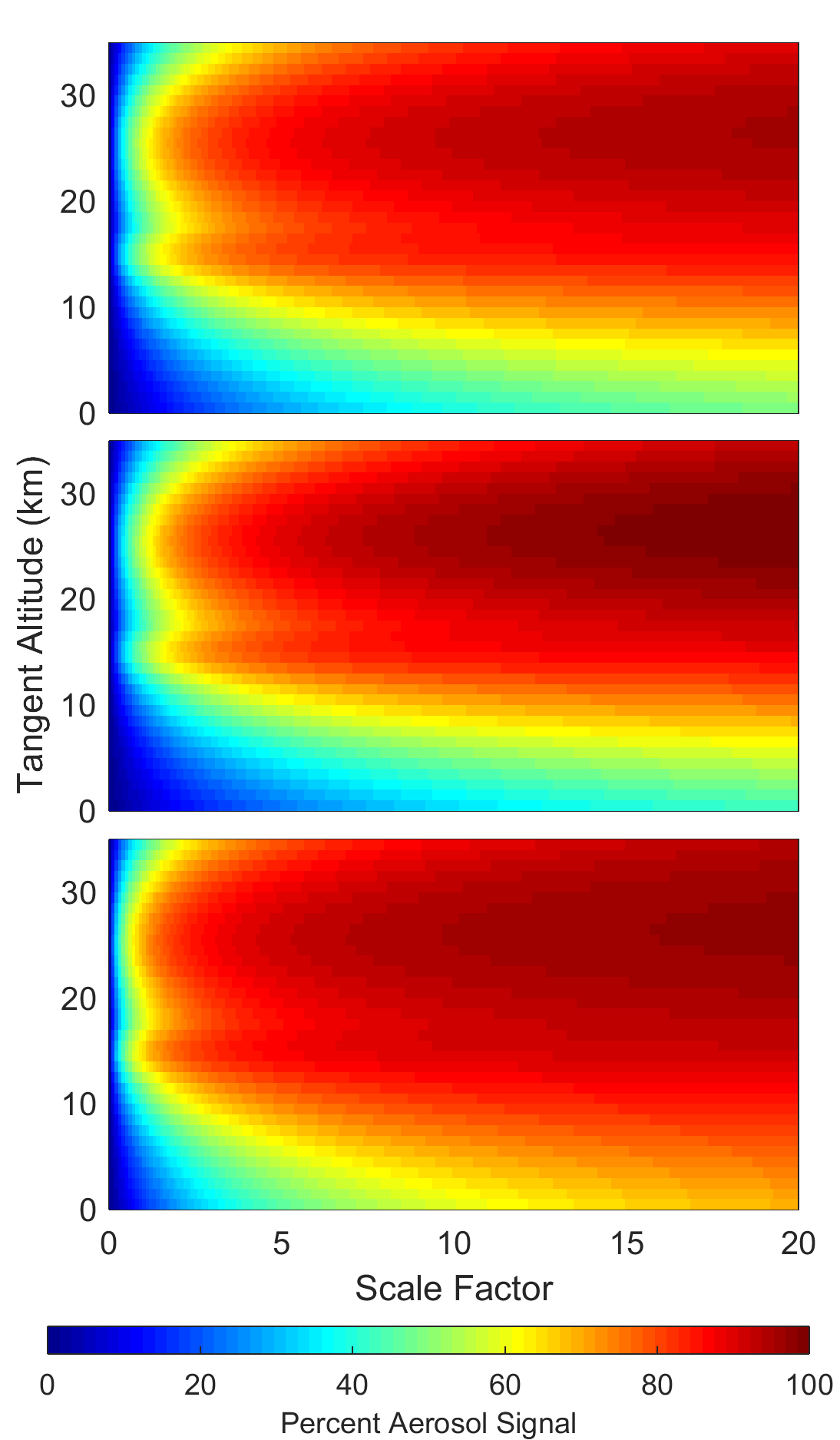
A similar analysis was performed using a variety of geometries at a range of altitudes to assess the aerosol signal strength. Figure 4-3 demonstrates the percent aerosol signal for 15.5 km tangent altitude with the background aerosol loading and an albedo of zero. A sharp difference is noted between 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, 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.



**Figure 4-4:** 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.

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 4-4, 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 4-5, 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.

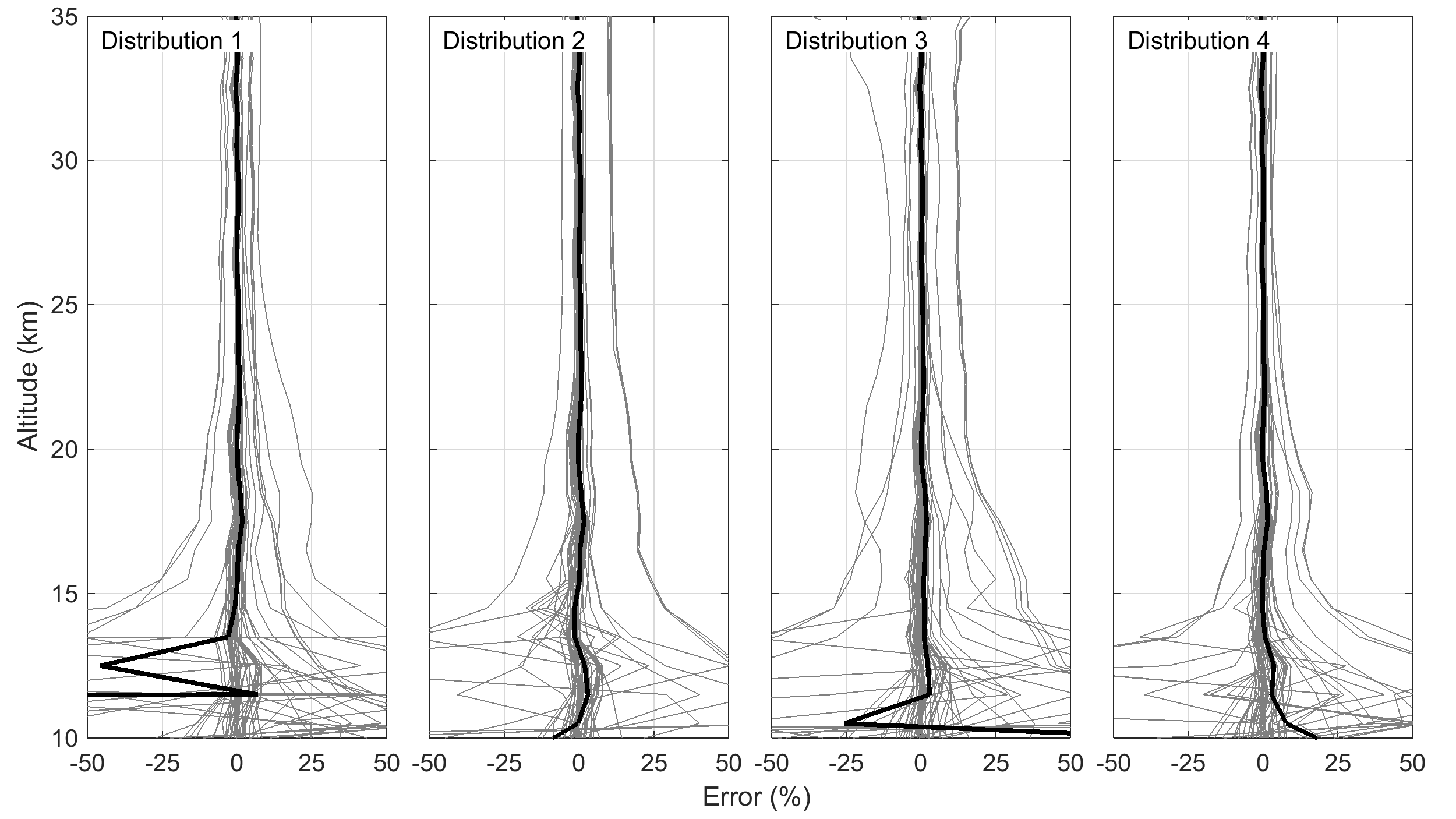


**Figure 4-5:** Similar to Figure 2 except only 750 nm wavelength is observed and the aerosol concentration has been scaled to determine where the signal saturated with aerosol.

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.

## 4.3.2 Retrievals

Retrievals were performed for all of the wavelengths listed in section 4.2.2, 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.



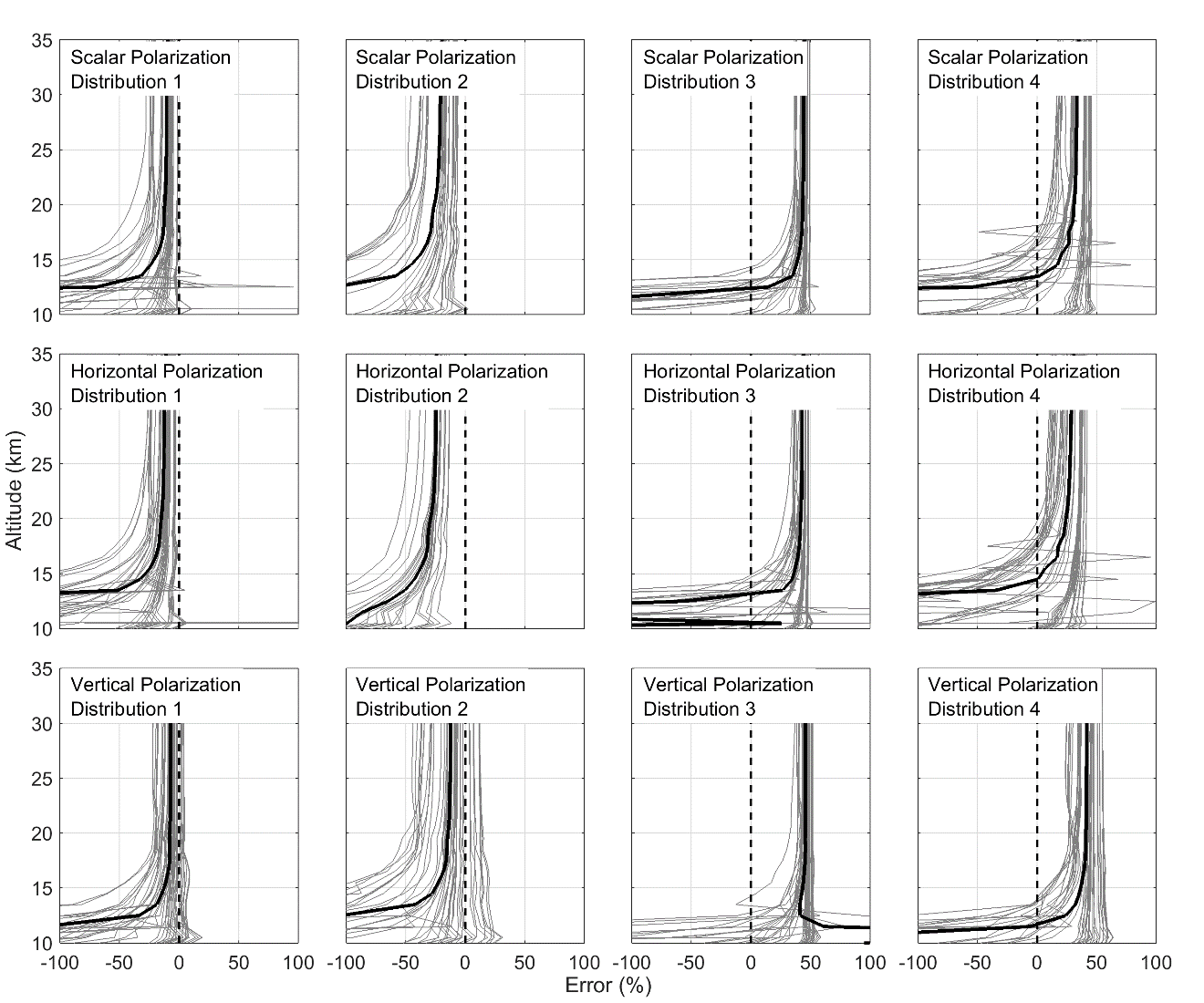
**Figure 4-6:** Percent differences of the retrieved aerosol profiles for the scalar retrieval versus the vector retrieval. Each column represents a different particle size distribution and the labels can be cross referenced in Table 1.

Retrievals with current limb scatter instrument use a scalar radiative transfer model for the retrieval 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

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| --- | --- |
|  | (4.4) |

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 4-6, 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 again the true aerosol extinction state. The 750 nm aerosol comparisons separated by polarizations states and particle size distributions can be seen in Figure 4-7. 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 dependent 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.



**Figure 4-7:** 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.

Now each of the distributions will be examined to notice any offsets from the true aerosol state. For particle size distribution one (see Table 4-1), retrieved aerosol extinction profiles are too large. For scalar, horizontal, and vertical polarizations had mean offsets of -9to -13%, -12 to -17%, and -6 to -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 to -28%, -24 to -31%, and -12 to -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.

Using the spectral variance of the aerosol profiles an Angström exponent (*Angström*, 1964) was attempted to be determine. The Angström exponent is method of determining particle size information due to a sensitivity of the scattering cross section from wavelength and should result in a linear trend in log-extinction log-wavelength space. Using retrieved aerosol profiles with identical geometries and particle size distribution an Angström exponent was attempted but resulting in values that were either much too large or small for a reasonable value. Addition work is required to determine if retrieving accurate particle size distributions is possible from linear polarized radiance measures for aerosol.

## 4.3.3 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. 3 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 12% 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 capability 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 4.2.2 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. Statistics trends were determined for each polarization and parameter to determine if there was a large effect on the overall precision depending of 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 how the precision changed based on the true state input parameters. The analysis was performed for the SSA, SZA, albedo, extinction type, fine mode type, percentage of coarse mode, and wavelength. The numeric value of the parameters can be looked up in Table 4-2.

**Table 4-2:** Parameters used in precision study.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Extinction Type Number | Extinction Loading | Fine mode Type | Fine Mode Radius (µm) | Fine Mode Width |
| 0 | Background | 0 | 0.04 | 1.8 |
| 1 | Nabro | 1 | 0.12 | 1.25 |

The results from this analysis can be seen for the 19.5 km altitude in Figure 4-8. When comparing the three different polarization, a similar trend occurs. On average, the scalar, horizontal and vertical polarization have similar percent error ranges for each parameter and generally differ by a few tenths of the percent. The scalar trends can be seen in Figure 4-8a-g, horizontal polarization trends in Figure 4-8h-n, and vertical polarization trends in Fig. 8o-u. Any major difference between the polarizations and altitudes will be noted when looking at each independence parameter.

For the SSA across all altitudes where the retrieval was performed an increase in uncertainty is observed as SSA is increases. At 14.5 km the mean uncertainty ranges from 0.8% at a SSA of 60o to 1.5% at a SSA of 180o, similarly for retrieval altitudes of 19.5 and 24.5 km ranges of 1.4-2.8% and 6.8-10.1% are noted. The 19.5 km case can be viewed in Figure 4-8a,h,o. The standard deviation of the also increases as the SSA increases. There is a dependence on the uncertainty of the retrievals to the SSA and forward scatter observations are preferred to reduce the uncertainty.

There is close to no dependence on the SZA when it come to the precision for all three polarizations. The mean and standard deviation remain mostly constant across the SZA angle. For the 14.5, 19.5 and 24.5 km altitudes mean ranges were observed of 1.2-1.6%, 2.0-2.5%, and 8.4-9.3% respectively for SZA from 15o to 75o. The 19.5 km altitude can be seen in Figure 4-8b,i,p.

For the albedo, from a change from zero to one resulted in a general decrease of mean uncertainties and standard deviation for all polarizations, however some altitudes of the horizontal polarization did not appear to have any trends with respect to albedo epically near the 18-22 km altitude regions. For the 19.5 km altitude (Figure 4-8c,j,q) the mean uncertainties for all three polarization cases varied between 2.3-2.7% for an albedo of zero and 1.8-2.2% for an albedo of one. With regards to polarization, the mean uncertainty of the vertical orientation for albedo was always a few tenths of a percent less than the other two polarizations. However, a full probe of this space has not been performed and it is unknown if the trend is linear with albedo as no other points were sampled.

Two extinction loads were used consisting of a background and a representative Nabro volcanic loading. The indices used in Figure 4-8d,k,r for the 19.5 km altitude can be looked up in Table 4-2. The mean uncertainty ranges are from background to Nabro loading for the 14.5, 19.5, and 24.5 km altitudes are 1.5-1.3%, 3.6-1.2%, and 9.8-8.4% respectively. When going from a background to a volcanic loading the increased extinction causes the mean percent error to become smaller due to the larger retrieved extinction. However this magnitude of the error on the two types of extinction level are approximately the same. This results in a trend that larger extinction loading yields smaller mean uncertainty and standard deviations but similar absolute errors.

Across the two fine modes which can be referenced in Table 4-2, there is a small dependence to the uncertainty from the two modes, but is mostly constant. It should be noted that the scans with a coarse mode were not filtered out from this specific parameter analysis and the full data set was used. For the fine mode dependence all three polarization were within a few tens of a percent of each other with the scalar radiance generally on the larger end and the vertical polarization retrievals on the smaller end. The 19.5 km altitude can be seen in Figure 4-8e,l,s.

With the existence of the strong coarse mode in the stratosphere a change in the precision occurs which is dependent on height. For the lower altitudes, for example 14.5 km altitude, the mean uncertainty changes by only a couple tenths of percent and increases when a coarse mode is added. However the effect of the standard deviations is dependent on polarizations. In the scalar and vertical polarizations cases the standard deviations decreases by 0.3% whereas the standard deviation of the horizontal polarization increases by 1.2%. At middle retrievals altitudes, for example 19.5 km, all three polarizations follow the same trend with an increase in the mean of the uncertainty with the addition of the coarse mode. The increase in the uncertainty is 0.9%, 1.0%, and 0.5% for the scalar, horizontal, and vertical polarizations. As well an increase in standard deviation is noted across all three cases, and can be observed in Figure 4-8f,m,t. The same is noted with higher altitude except with even a greater increase of the mean by approximately 3% at 24.5 km.

For wavelength the same trend occurs for all retrieved altitudes, as the wavelength increases the uncertainty in the aerosol retrieval decreases quite substantially for all three polarization cases. This can be seen Figure 4-8g,n,u.

After completing the analysis it was determined that all three polarizations exerted approximately the same absolute effect on the precision. 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.

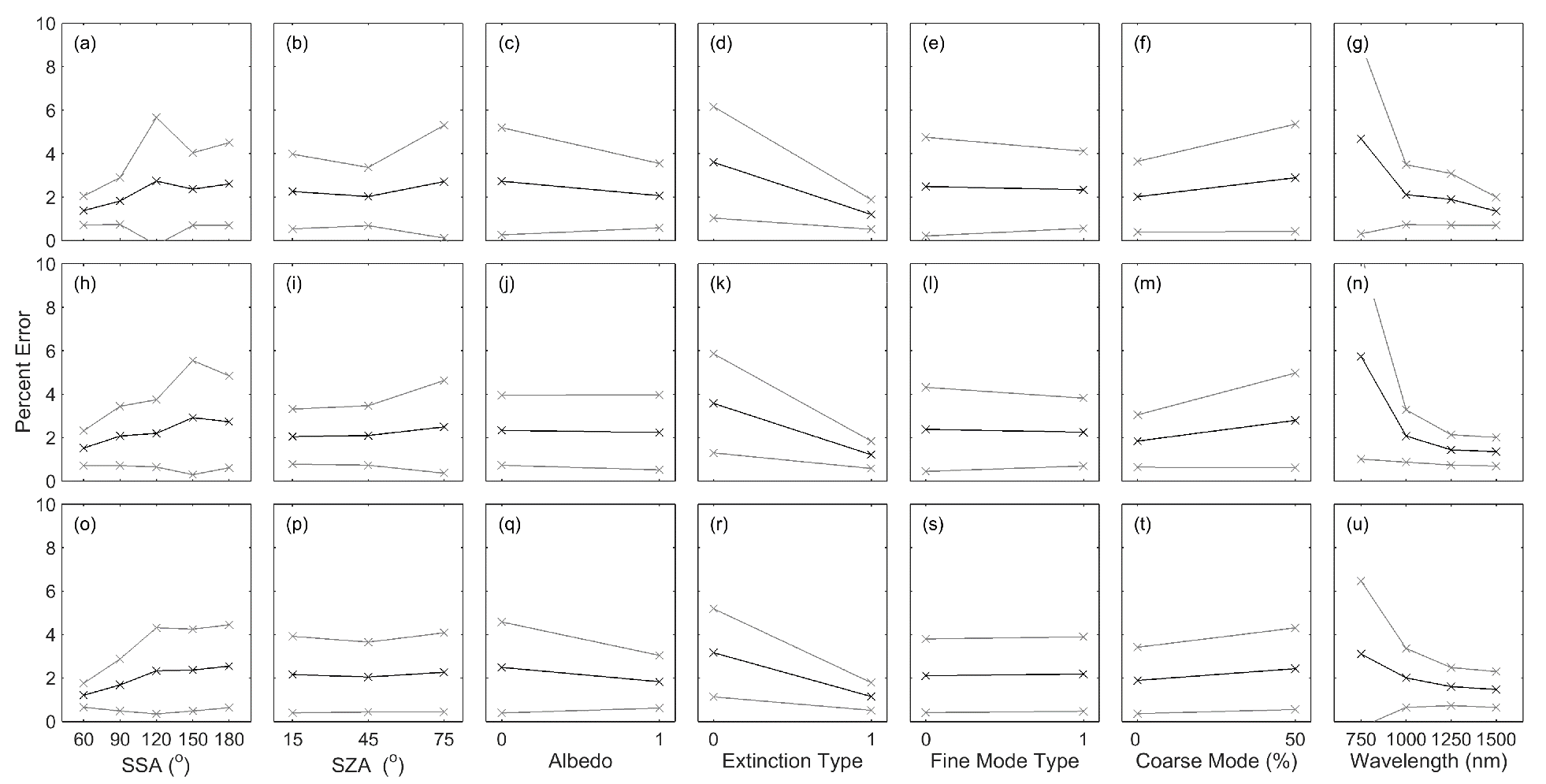
As a final note the sensitivities of aerosol signal noted in section 4.3.1 was not accounted for in this analysis which in reality would alter the precision for an identical instrument measuring opposite polarizations. If we assume the instrument is calibrated such that the exposure time is set to measure 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 varying depending on the aerosol extinction profile and the viewing geometry.

# 4.4 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 contains 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.



**Figure 4-8:** Trend analysis for the 19.5 km retrieval altitude. Then black points are the mean precision value for the bin, and the grey point is one standard deviation from the mean. Panels (a) through (g) are for the scalar radiance, (h) through (n) is the horizontal polarization, and (o) through (u) are for the vertical polarization.