Polarization Study

B. J Elash, A. E. Bourassa, L. A. Rieger, Seth?, Dan?, D. A. Degenstein

**Abstract:**

# **1 Introduction**

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

In order to compare the effect of polarization on the sensitivity to model to accurate computer polarized radiance models is required as well as suitable set of aerosol profiles for the retrieval. In this section the SASKTRAN model used for the analysis with be discussed and the aerosol scenarios used for the analysis.

## 2.1 SASKTRAN model

I figured I would ask Dan or Seth to write this portion as they know the details better than I do.

## 2.2 Aerosol Scenarios

The range 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 consternations 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. To probe a large portion of this space a series of scenarios were derived.

To probe the aerosol space two profile and four particle size distribution were used. The two profiles are a background aerosol extinction profile typically during the volcanically quiet period starting in 1997, and the second profile is a representative volcanic profile after the Nabro eruption in 2012 with a higher sulfur injection from the eruption at approximately 20 km. Both profile can be observed in Figure 1. A log-normal particle size distribution was selected with two fine modes and one coarse mode which can be seen in Table 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 representation of two background aerosol particle size distributions and the coarse mode is a representation the effect of a volcanic eruption on the size of the aerosol droplets (Deshler et al, 2003).

To scan the entire geometry a range of Solar Zenith Angles (SZAs) and Solar Scattering Angles (SSA) were selected. The range of SZA are 15 o, 45 o, and 75o and SSA of 30 o, 60 o, 90 o, 120 o, 150 o, and 180o cover the a large portion of the possible geometries for limb scatter. An albedo of 0 and 1 were used to determine how ground reflectance effect aerosol sensitivity on polarization measurements. 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 TODO:ADD CITATIONS) and from work done by Rieger er al. (2014) has shown near infrared is needed to discern particle size from limb scatter measurements.

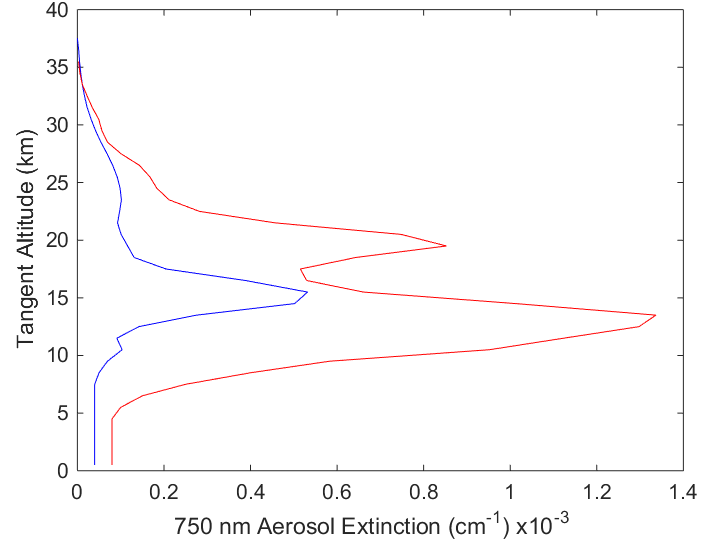


Figure 1: The two aerosol profiles used in this study. The blue is a background aerosol extinction levels, and the red curve is a representative aerosol profile after the Nabro eruption.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| 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.

## 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 (Elash et al., 2015) use an acousto-optic tunable filter 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 scaler radiance. The three polarizations used will be define as the following: radiance that aligned with the horizon will be known as the horizontal polarization and radiance that perpendicular the horizon will be known as the vertical polarization. The third polarization used the total radiance which will be known as the scaler radiance and is used as the reference case. Using the Stokes parameters, the scaler radiance is defined as , the horizontal polarization is given by and the vertical polarization is given by .

The study looks at the problem is three section. How does the percent of the aerosol signal compare to the overall radiance for a variety geometries and aerosol profiles? How does the polarization affect the ability to retrieve aerosol from a simulated measurement using a consistent particle size distribution? And how does the sensitivity 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 percent of the radiance that is inherent to aerosol. The model is ran using a polarization mode that accurately models the polarized radiance for the first three orders of scatter, then the scattering are assumed to be completely scaler in nature. The model is ran with a nominal atmosphere that consists of molecular air, ozone, and NO2 which is kept constant, and with a variable altitude and albedo. The sensitivity was determined by calculating the radiance without aerosol in the model, , and the radiance including the aerosol known as the total radiance, , and using the difference between the total radiance and nominal radiance would yield the aerosol radiance look at a percent of the signal that come from aerosol gives the relative sensitivity for aerosol with a particular polarization in the form

From this information it can be determined where the aerosol contributes the large percentage of the signal. On the other hand a look at the loss of radiance will be looked at when using a polarized measurement to a scaler instrument to determine the required increase in exposure time for the polarized measurements.

To determine the effect of polarization on the retrieval a retrieval method will be used similar to aerosol extinction retrieval by Bourassa et al. (2012). A minor change to the algorithm is 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. For the retrievals a simulated measurement radiance profile will be calculated using the SASKTRAN-HR model with a 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 multiplicative algebra reconstruction technique for all three polarization states. Additionally, a retrieval will be performed with the scaler SASKTRAN-HR model to see if there is a large discrepancy between using the scaler and the polarized model to retrieve aerosol profiles from a scaler measurement. For each aerosol retrieval the Ozone, NO2, and albedo are set the same in the modeled measurement but the aerosol particle size is to be set to 0.08 µm mode radius and 1.6 mode width. The assumption of an incorrect particle size is very common in current limb scatter instruments (i.e. OSIRIS and SCIAMACHY) will be used to see how the different polarizations are sensitivity to particle size distributions and if this incorrect assumption greatly affects the retrieved extinctions.

Lastly, In order to check the precision of the retrieved aerosol profile an error analysis of the revivals will be performed. The method used for this analysis is one presented by Bourassa et al. (2012) 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.

# 3 Analysis

## 3.1 Aerosol Sensitivity

The SASKTRAN-HR model was run for many different geometries and 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 sensitive to aerosol.

First, contribution from aerosol was analyzed across wavelength and over a series of altitudes. The aerosol profile used is the background aerosol profile with particle size distribution one. As expected as wavelengths become longer the percent aerosol increased, but as seen in Figure 2 which is a foreword scattering case (SZA of 45o, SSA of 60o), the percentage of the signal that is cause by the aerosol has increased in the vertical polarization whereas the horizontal polarization has less sensitivity to aerosol. It should be noted that the opposite effect is seen for a backscatter case. Another interesting feature to note is that it appears that the vertical polarization reached a maximum of 70% aerosol contribution at approximately 1200 nm at 25 km then falls off as wavelengths get longer. Where the aerosol signal becomes monotonically stronger as wavelength increases for scaler and horizontal polarizations.

Since the foreword and backwards scattering cases effect the horizontal and vertical polarizations aerosol signals in an opposite fashion. Using an altitude of 15.5 km altitude and processing the percent aerosol signal across a series of SZA and SSA (Figure 3) to determine where the significant of the SSA on the aerosol signal. What is important is the aerosol signal between the horizontal and scaler radiance is not very different and for most geometries only vary in percent aerosol signal by a couple of percent at most. For the vertical polarization measurement, the signal pertains a significant portion of aerosol sensitivity for the foreword scatter case, especially at shorter wavelengths. However is should be noted that modeling the vertical polarization with a SSA of 90o is difficult to calculate accurately and the results at this point should not be trusted (TODO: ADD cites). However slightly better sensitivity The SZA has a small effect on the percentage of aerosol signal and various approximately monotonically across all three polarizations.

The sensitivity of aerosol between horizontal and scaler radiances is approximately the same and the vertical polarization has better sensitivity in the forward scattering case than the backscatter case. However, by only measuring a linear polarization results in a loss of overall radiance or signal. In Figure 5 the ratio of the total polarized modeled over the total scaler radiance is shown as a percentage for a SZA of 45o and SSA of 60o with a background aerosol profile. When using a horizontal polarization for an instrument would result in at shorter wavelengths only observing approximately 58% of the signal and at longer wavelengths this increases to approximately 66%. For the back scatter case a percent of the measure signal increases slightly to 74% at short wavelength and 80% at long wavelengths. The loss on signal would need to be accounted for by a small increase, a mean of approximately 30%, to exposure times. For the vertical polarizations however, the increased aerosol signal in the foreword scatter case is met with a loos in overall signal of up to 70% and for the backscatter case a decrease of up to 85% of the total signal. This is a significant loss of signal that will essentially double an instrument exposure time, which depending on the expected exposure time for an optical instrument may lead to unacceptably long exposure time 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 the all polarizations the rate of increase of aerosol signal increases substantially until approximately 90% of the radiance signal id from aerosol then it is considered to be saturated. This corresponds to a 0.1% increase in aerosol signal for a 0.1 increase of scale factor. For scaler 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 foreword scatter geometry we see a cap of aerosol sensitivity at 4.4 time the background aerosol layer. For a large volcanic eruption would limit the aerosol concentration profiles that could be retrieved.

The vertical polarization yields significantly more aerosol signal in the foreword scattering case compared to 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 be not as effective as measuring aerosol during large volcanic eruptions.

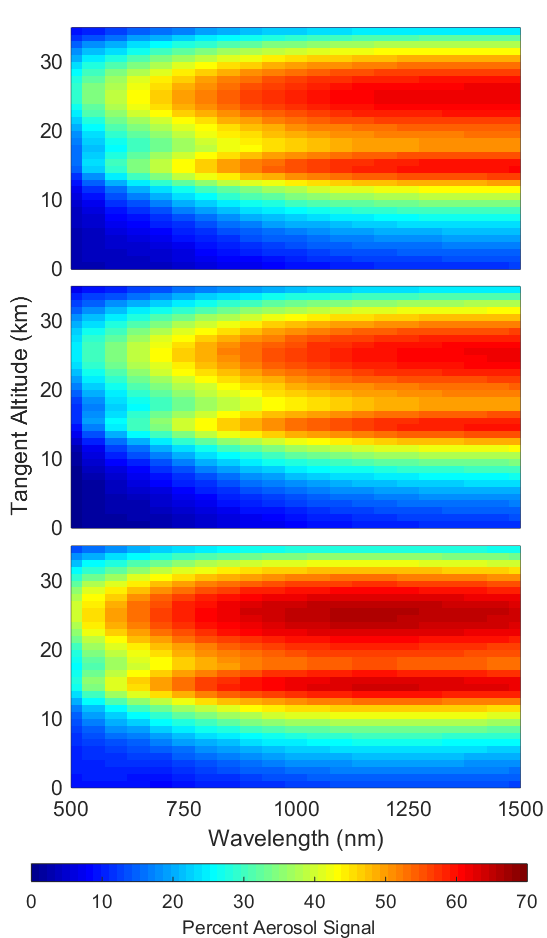


Figure 2: A computation of the percentage of aerosol radiance signal over the total radiance for a series of three polarizations. The top, middle, and bottom figures are the scaler, horizontal polarization, and vertical polarization respectively. The geometry for the simulation is set up with SZA of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

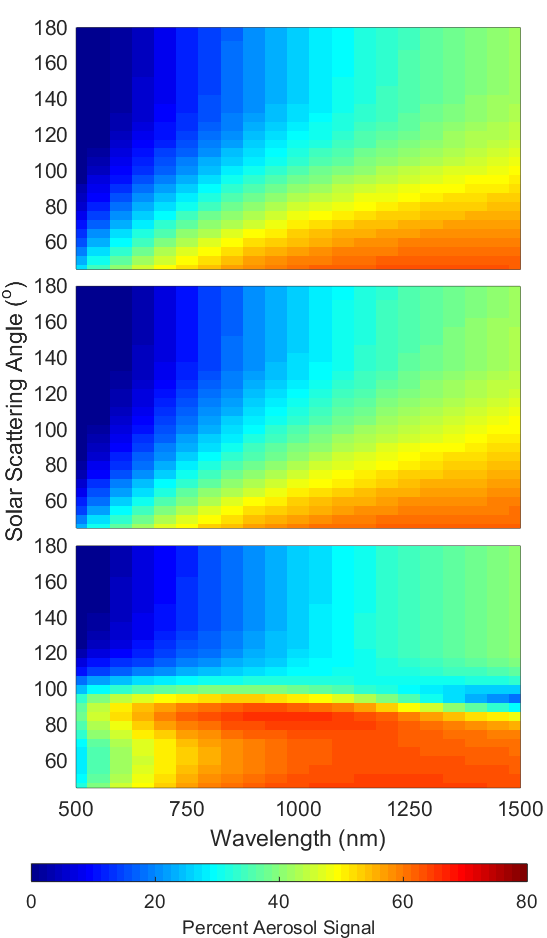


Figure 3: A computation of the percentage of aerosol radiance signal over the total radiance for a series of three polarizations. The top, middle, and bottom figures are the scaler, horizontal polarization, and vertical polarization respectively. The geometry for the simulation is set up with SZA of 60o at a tangent point of 15.5 km with an Albedo of 0 and using the background aerosol profile.

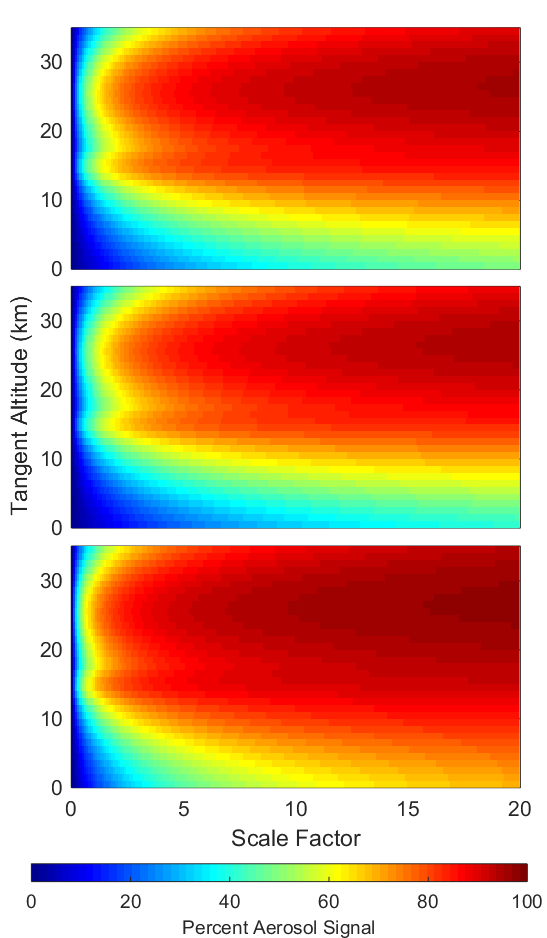


Figure 4: A computation of the percentage of aerosol radiance signal over the total radiance for a series of three polarizations. The top, middle, and bottom figures are the scaler, horizontal polarization, and vertical polarization respectively. The geometry for the simulation is set up with SZA of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

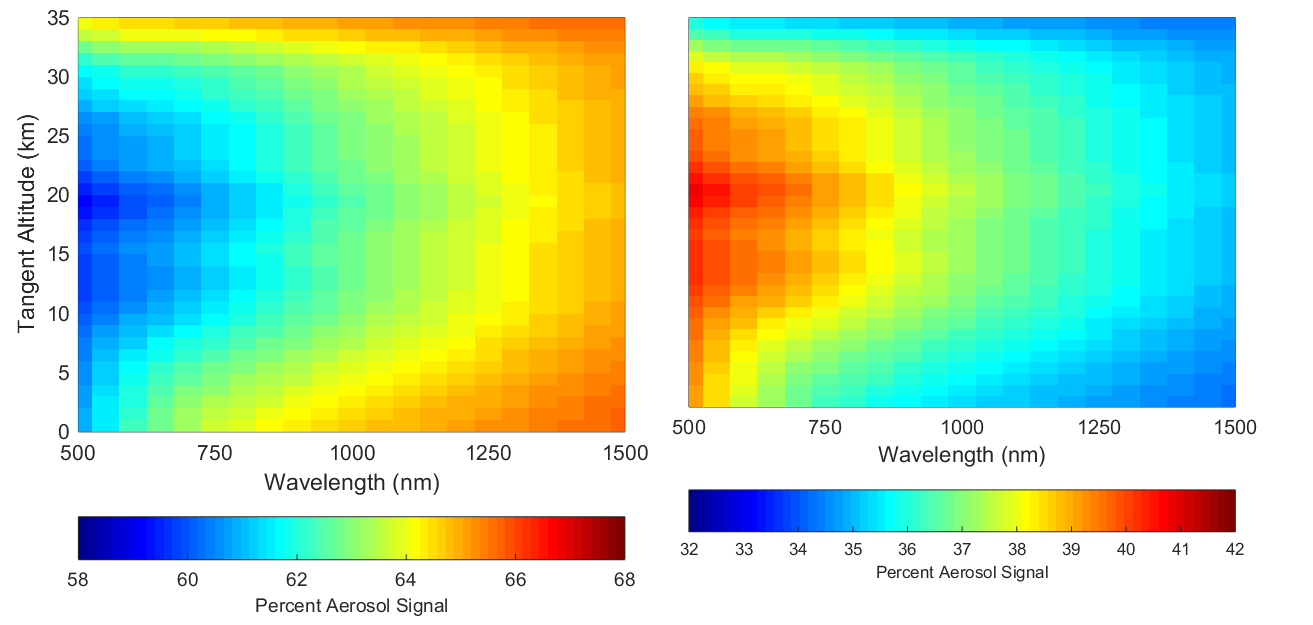


Figure 5: A percent of the linear polarized radiances to the scaler radiance, the left and right figures are the horizontal and vertical polarizations respectively. The radiances were calculated with a geometry of 60o SZA and 45o SSA with an albedo of 0 and using the background aerosol profile. Note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

## 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 comment on the other wavelengths necessary when deviations to the norm occur.

For the reference case, the scalar radiance, aerosol profile can be retrieved using either the scaler or vector SASKTRAN-HR mode. As such aerosol retrievals were determined for both model modes using the same input radiances. A compression between the retrieved extinctions for the scaler 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 reveals 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 scaler radiance due to polarization interactions but further investigation is required. However, overall the agreement between the retrievals using the scaler 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 scaler 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 then the true state. For the three tested polarizations aerosol 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 7. It should be noted that geometries with SSA of 90o have been removed for the vertical polarization due to the inaccuracies in modeling this case which biased the results.

For particle size distribution one 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, slight larger, but a higher variance is seen. The offset for distribution two are 20-28%, 24-31%, and 12-16% for the same polarization from 17 to 35 km. For the corresponding particle size modes with a coarse mode (distributions 3 and 4) are seen similar variances between the similar fine modes but the aerosol offset is much larger for all three polarizations. The retrieved aerosol extinctions profiles are much less than the true state and for distributions three and four mean offsets of 30-45%,

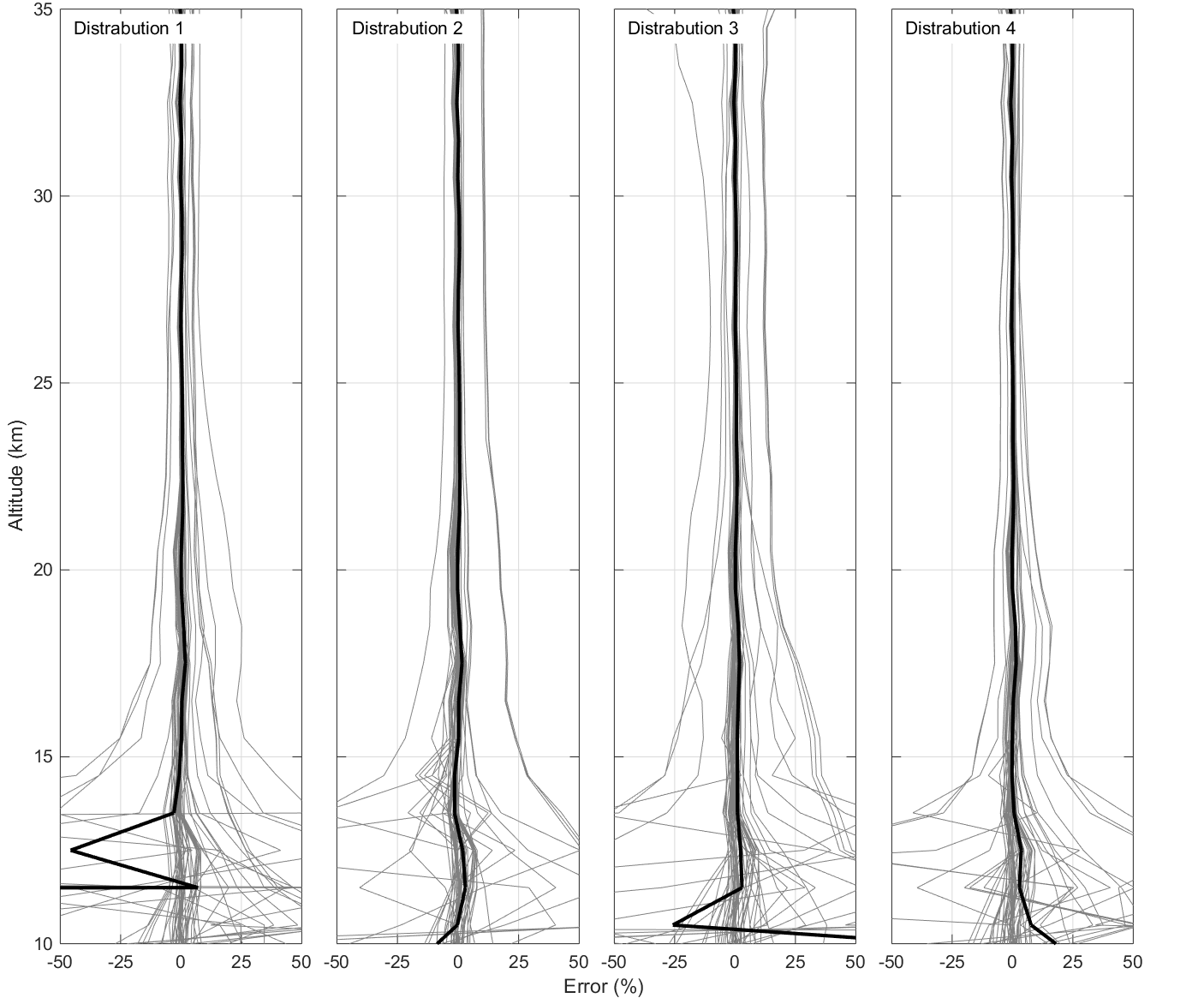


Figure 6: Percent differences of the retrieved aerosol profiles for the scaler retrieval versus the vector retrieval. Each column represents a different particle size distribution and the labels can be cross referenced in Table 1.

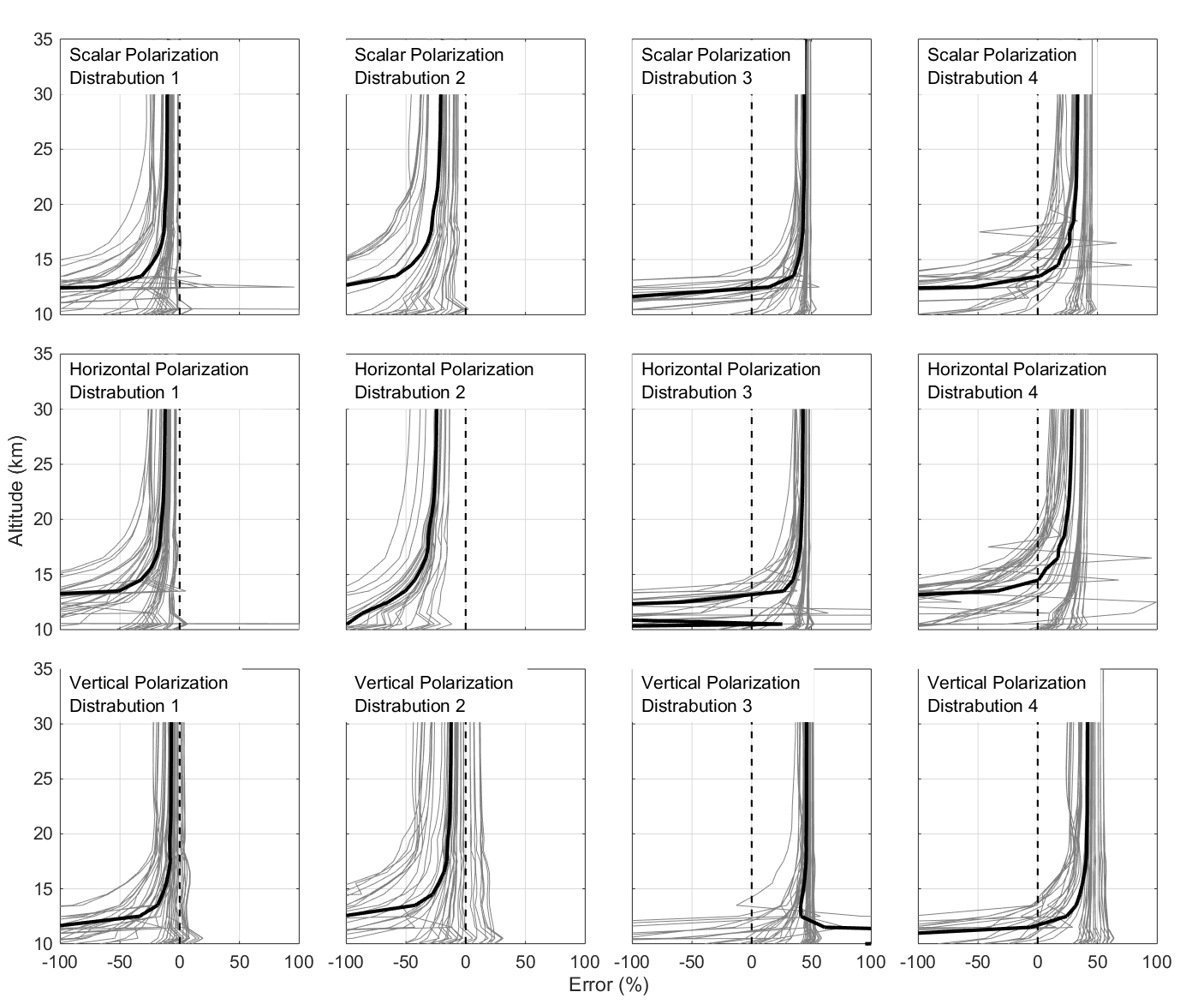


Figure 7: The retrieved aerosol profiles for each unique combination of geometry and aerosol profile are compared again the known original sates. The plot are separated into 16 cases. The four columns represent the four polarization used for the analysis and from left to right is the scaler radiance with the scaler SASKTRAN-HR model, the scalar radiance with the polarizations models, the horizontal polarization, and the vertical polarization. The rows represent the four particle size distributions from one to four from top to bottom as listed in Table 1.

## 3.3 Error analysis

TO CREATE FIGURE

Figure 8: Not sure have not been able to complete this yet. Will discuss in Email.

# **4. Conclusions**

# Acknowledgements