Aerosol sensitivity with linear polarized measurement in limb scatter geometry

B. J Elash, A. E. Bourassa, L. A. Rieger, S. R. Dueck, D. A. Degenstein

**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, such as ALI and ALTIUS, recording linear polarization a study to determine the optical geometry has been underwent. A sensitivity study, aerosol retrieval analysis, and precision analysis have been performed for the scalar, horizontal, and vertical polarizations.**

# **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 cause by a series of small-scale, tropical volcanos (Hofmann et al., 2009). Stratospheric aerosol causing a cooling effect by scatting 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 monitor on a global scale from satellites for decades from instruments 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 results 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 and SCIAMACHY measure radiance from the limb and use inversion techniques to determine aerosol profiles (TODO: ADD CITES). 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) (Elash et al., 2015). Both instruments use acousto-optic tunable filters to select the measured wavelength and only transmitted 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.

# **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 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 et al. (2014) has shown near infrared is needed to discern particle size from limb scatter measurements.

## 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 without full knowledge of particle size information as the scattering at this geometry is primarily attributed to small component of a phase function.

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.

## 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 small phase function contribution of aerosol to the overall radiance. By assuming an incorrect phase function causes a relatively large change in the phase function resulting in a strong dependence on particle size and to remove this bias from the results these retrievals were removed from the analysis. However using a look geometry with a SSA of 85o or 95o eliminates the bias seen at the 90o.

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 were 42-44%, 40-43%, and 45-46% for distribution three and 26-33%, 22-29%, and 40-42% for distribution four. Furthermore, as wavelength increases an approximately 3-5% increase in offset is observed for the retrieved aerosol profiles for each polarization. Using the method proposed here, decent aerosol profiles can be retrieved when only a fine mode or background aerosol layer period, since current instruments only agree to each other within 20-30%. However, when a coarse mode is present in the true state, the retrieval significantly underestimates the amount of aerosol in the atmosphere. Since volcanic eruptions are the main reason for a perturbation in the size distribution this can essentially lead to an underestimation of aerosol extinction after a significant eruption which can cause noticeable climate forcing effect.

## 3.3 Precision analysis

Using SASKTRAN-HR the Jacobians for all the retrieved were calculated, which were then inverted to determine the gain matrix and used in Eq. 3 to determine the precision. It should be noted that not all of the Jacobians cold be stability inverted and were removed from the data set. Unfortunately, this resulted in a large portion of the SSA 30o not to invert properly and left too few for accurate statistics and were removed since there was the smallest number of these scan at this SSA since the geometry only exist when the SZA is 75o in the study. This resulted in a loss of 12% of all of the retrieved scans.

For the covariance of a value of 0.2% was chosen for each altitude of the of the measurement vector. The diagonal of the covariance matrix was 0.4% since it consisted of the altitude measure and the error in the reference altitude. The cross terms of the covariance matrix was 0.2% to represent the error in the normalization altitude. Calculated all of these values resulted in very large and noisy uncertainty for the 500 nm wavelength which biased the results for other parameters and was removed when doing trend analysis. The remaining profiles were used to determine the percent error ta each altitude and determine how the precision changed over look at how the used parameters. The analysis was performed for the SSA, SZA, albedo, extinction type, fine mode type, percentage of coarse mode, and wavelength. The value of the parameters can be looked up in Table 2.

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

For the SSA for all altitudes where the retrieval was performed as increase in uncertainty is observed as SSA is increases and the larges uncertainty occurs when the case if complete backscatter. 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% respectively. The 19.5 km case can be viewed in Fig. 8a,h,o. The standard deviation of the also increases as the SSA increases. From this there is a dependence on the uncertainty of the retrievals to the SSA and forward scatter observation are preferred to reduce uncertainty.

There is close to no dependence on the SZA when it come to the uncertainty 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. The 19.5 km altitude can be seen in Fig. 8b,I,p.

For the albedo, from a change from zero to one resulted in a decrease of mean uncertainties and standard deviations on average, however some altitudes of the horizontal polarization did not appear to have any trends with respect to albedo. For the 19.5 km altitude (Fig. 8c,j,q) the mean uncertainties 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.

For the extinction type, two were used in the study a background and a representative Nabro loading. The indices used in Fig. 8d,k,r for the 19.5 km altitude can be determined in Table 2. When going from a background loading to a volcanic loading the increase causes an increase in extinction that causes the mean percent error to smaller due to the larger retrieved extinction. This results in a smaller preceded mean uncertainty but they are on the order of the same size in absolute magnitude. This result in a trend that larger extinction loading yields smaller mean uncertainty values. 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.

Across the two fine modes which can be referenced in Table 2, there is a small dependence to the uncertainty from the two modes, but the mostly constant. It should be noted that the scan with a coarse mode were not filtered out from this specific analysis and the full set was used. For the fine mode dependence all three polarization were within a few tens of each other with the scalar radiance generally on the larger end and the vertical polarization retrievals on the smaller mean uncertainly. The 19.5 km altitude can be seen in Fig. 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 14.5 km altitude the mean uncertainty changes by only a couple tenths of percent increase as a coarse mode is added, however the effect of the standard deviations is dependent on polarizations. In the scalar and vertical cases the standard deviations decreases 0.3% whereas the standard deviation of the horizontal polarization increases by 1.2%. At 19.5 km all three polarization 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 Fig. 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. As can be seen Fig. 8g,n,u. This would result in instruments that can measurement further into the NIR an advantage when determining the precision of the aerosol retrievals.

For precise aerosol retrievals, an instrument should primarily be designed to capture forward scatter signal (SSA less than 90o) at longer wavelengths into the NIR. These measurements would result in the highest precision possible. For the aerosol profile itself it is preferred to have a volcanic loading with only a fine mode and no coarse mode. In reality a volcanic eruption inherently forms a coarse mode and the volcanic loading with no coarse mode is not physically possible. Choice of polarization does not have a great effect on the precision of the retrievals with the overall uncertainty generally varying by only a few tenths of the percent between the polarization cases.

# **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 the geometry of the orbit. The overall best situation would be an instrument that measures forward scattered light in the vertical polarization or the polarization normal to the horizon. In this orientation the radiance measurement has good sensitivity to aerosol across all altitude greater than 13 km. However, the increased sensitivity especially at the shorter wavelengths fall 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, without correct knowledge of particle size information scattering angles at 90o contain a bias to the retrieved aerosol extinction. Second, a large loss of the overall signal is lost from measuring the vertical polarization, up to 68% which would increase exposure times. Depending on instrument specifications, the required increase in exposure time may result in unacceptable high values.

If more signal is required 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% which is considerable better than the vertical polarized case.

Further work is needed to be able to determine if the systematic differences between the retrieved aerosol extinction offsets and the original profile can be corrected through the use of some particle size retrieval’s method. As an Angstrom exponent fit does not yield accurate particle size information from the direct retrievals.

As a final note the agreement between the scalar and vector SASKTRAN-HR model are generally within 2% of each other with the aerosol retrievals are promising in that the inclusion of polarization in the model does not cause a large change to the retrieved aerosol profiles. As requiring the use of the vector model could result in a doubling in processing time.

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# References

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

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.

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

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.

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.

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

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

Table 2: Parameters used in precision study.



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.

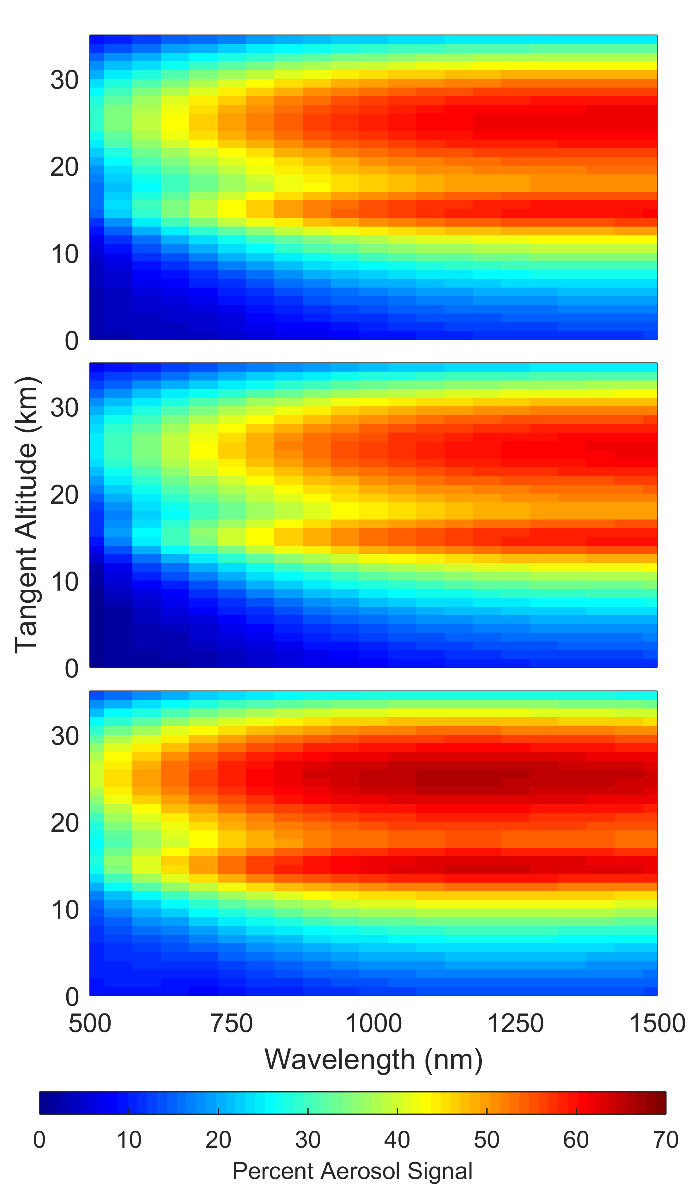


Figure 2: A computation of the percentage of aerosol radiance signal over the total radiance for a series of three polarizations. The top, middle, and bottom figures are the scaler, horizontal polarization, and vertical polarization respectively. The geometry for the simulation is set up with SZA of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

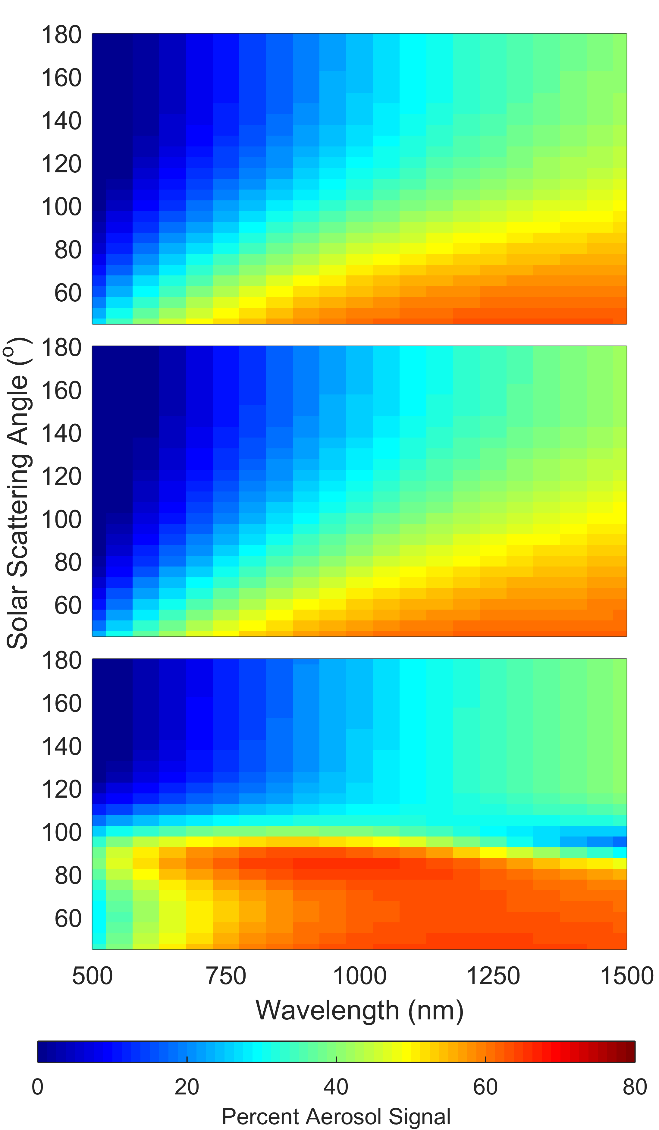


Figure 3: A computation of the percentage of aerosol radiance signal over the total radiance for a series of three polarizations. The top, middle, and bottom figures are the scaler, horizontal polarization, and vertical polarization respectively. The geometry for the simulation is set up with SZA of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

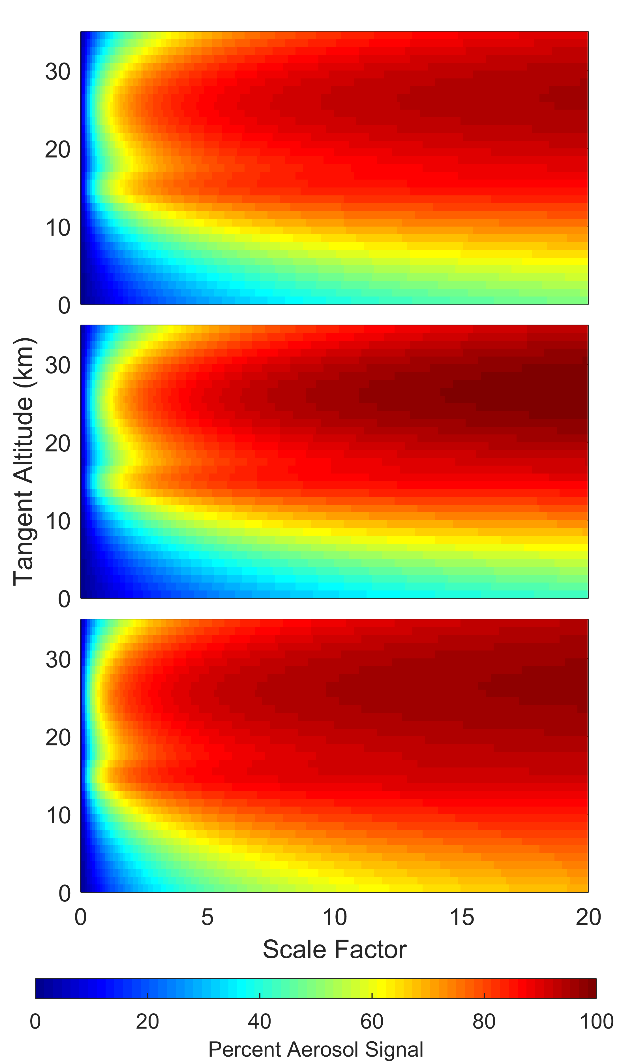


Figure 4: A computation of the percentage of aerosol radiance signal over the total radiance for a series of three polarizations. The top, middle, and bottom figures are the scaler, horizontal polarization, and vertical polarization respectively. The geometry for the simulation is set up with SZA of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

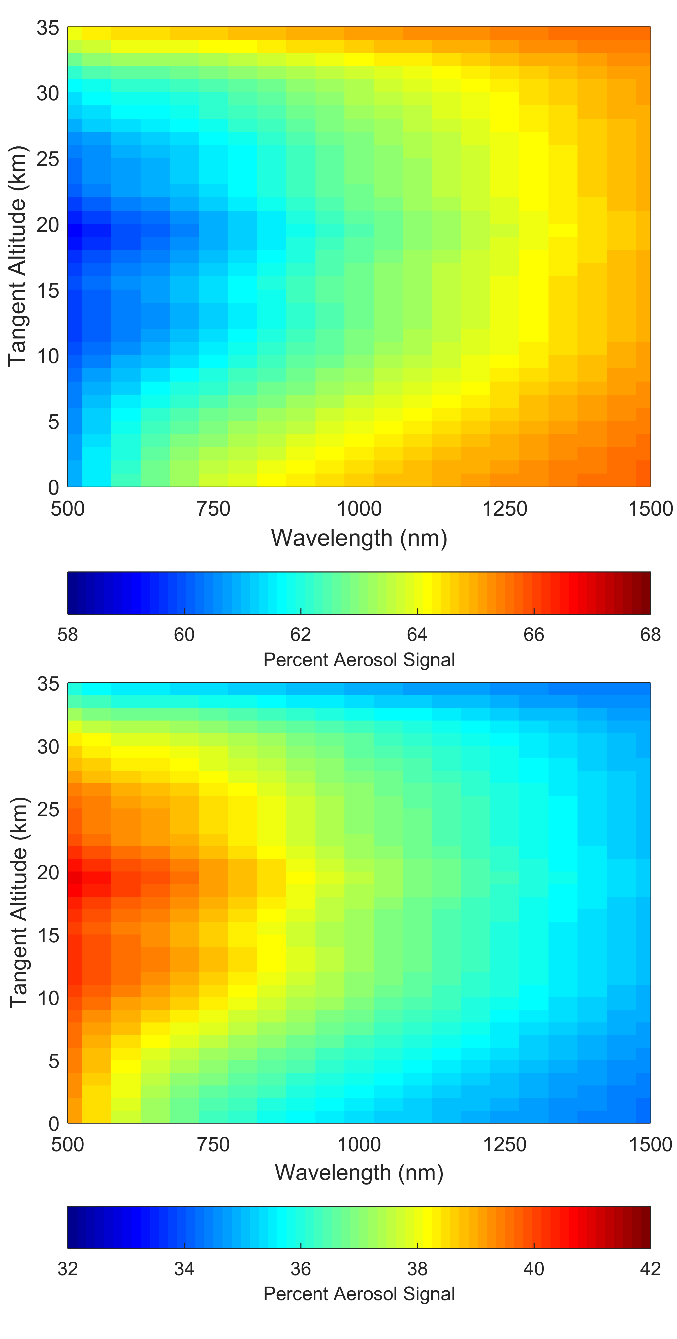


Figure 5: A percent of the linear polarized radiances to the scaler radiance, the top and bottom figures are the horizontal and vertical polarizations respectively. The radiances were calculated with a geometry of 60o SZA and 45o SSA with an albedo of 0 and using the background aerosol profile. Note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



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

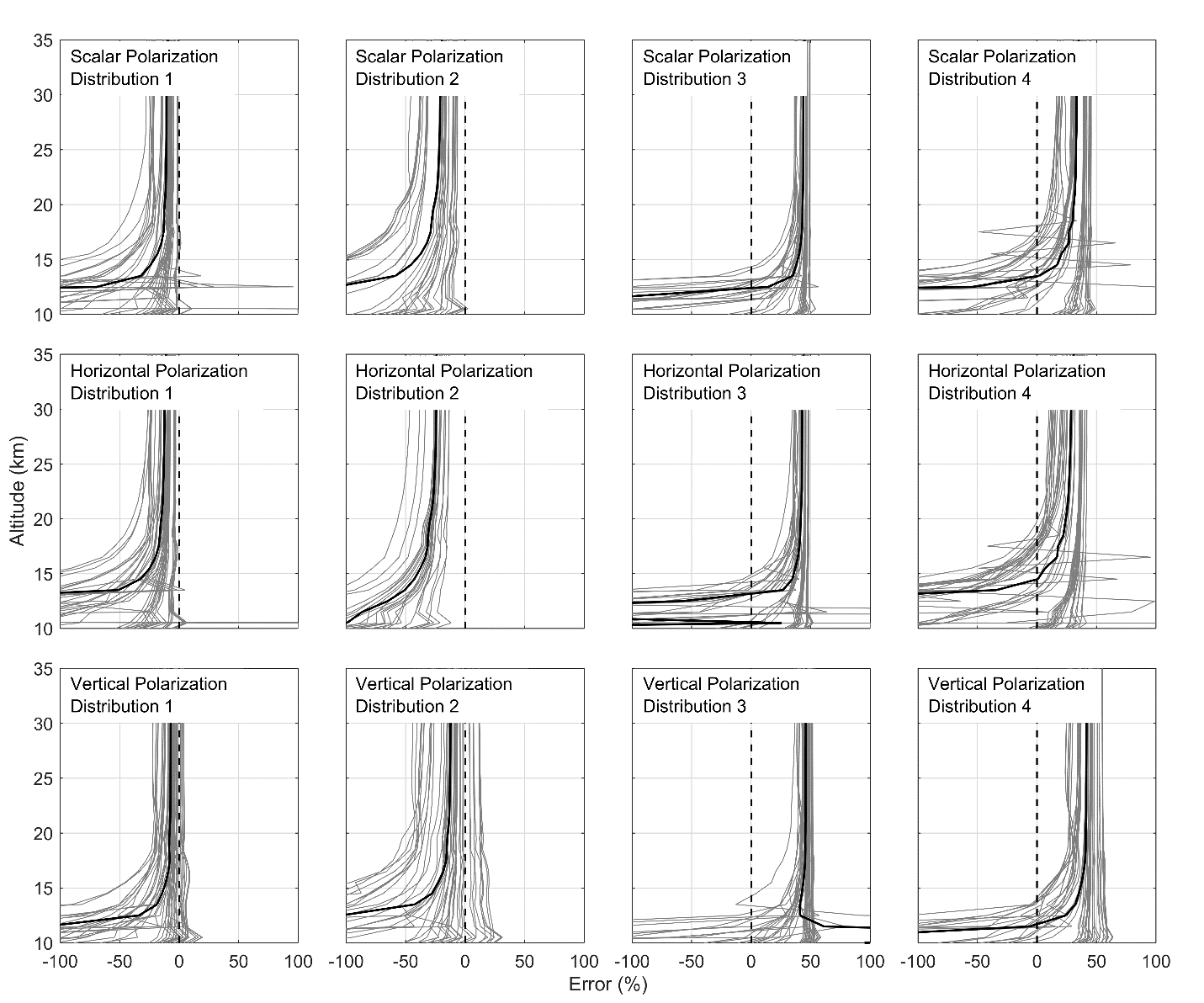


Figure 7: The retrieved aerosol profiles for each unique combination of geometry and aerosol profile are compared again the known original sates. The plot are separated into 16 cases. The four columns represent the four polarization used for the analysis and from left to right is the scaler radiance 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.

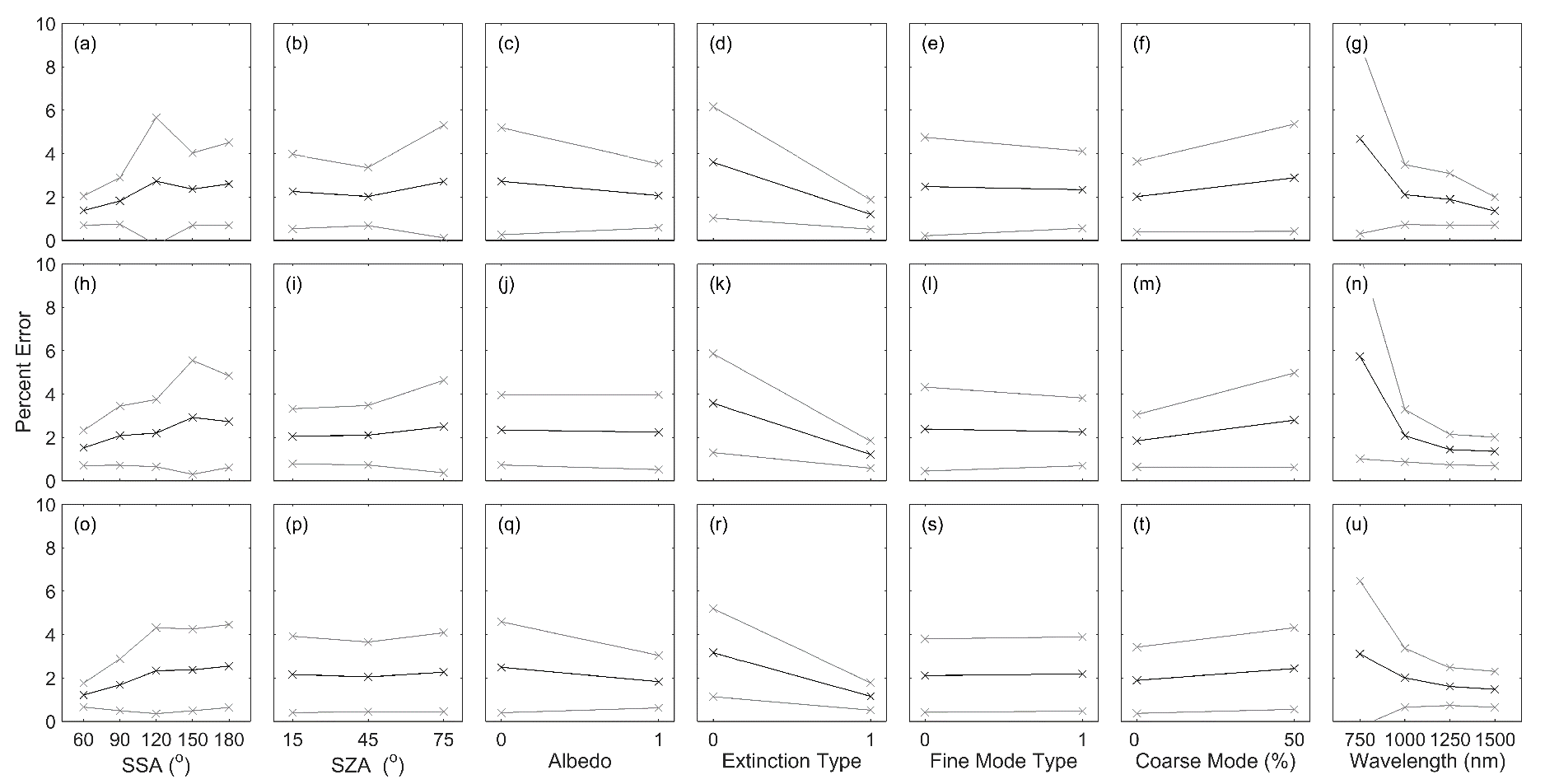


Figure 8: Trend analysis for the 19.5 km retrieval altitude. Then black points are the mean precision value for the bin, and the grey point is one standard deviation from the mean. Panels (a) through (g) are for the scalar radiance, (h) through (n) is the horizontal polarization, and (o) through (u)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