

The Aerosol Limb Imager: Multi-spectral polarimetry for the stratosphere

Adam E. Bourassa^a, Doug A. Degenstein^a, Daniel J. Zawada^a, Landon A. Rieger^a, Daniel S. Letros^a, and Paul. R. Loewen^a

^aInstitute of Space and Atmospheric Studies, University of Saskatchewan, Saskatoon, Canada

ABSTRACT

The Aerosol Limb Imager (ALI) is one of a group of three Canadian optical satellite instrument concepts that are part of the Canadian HAWC (High altitude Aerosol, Water vapor, and Cloud) mission. The mission is currently in Phase A development and will be launched into low earth orbit in 2031. ALI is a novel multi-spectral polarimetric imager designed to measure aerosol properties above clouds in the upper troposphere and stratosphere with high spatial resolution. These aerosols have a direct effect on climate and are highly variable due to volcanic and wildfire sources. The ALI instrument, which images limb scattered sunlight in the visible and near infrared spectral range, will be the first of its kind to incorporate high accuracy polarimetry. This has several scientific advantages including discrimination of clouds and aerosol types as well as providing additional valuable information on the aerosol particle size distribution. This presentation will showcase the benefit of the combined polarimetric and spectral information and discuss the challenges with the optical design concept including stray light mitigation and high dynamic range of the imagery.

Keywords: stratospheric aerosol, limb scattering, polarimetry, aerosol particle size

1. INTRODUCTION

1.1 The HAWC Mission

The High-altitude Aerosols, Water Vapour and Clouds (HAWC) mission is a Canadian Space Agency Earth-observation mission being developed by Canada for launch into a three year mission in low earth polar orbit in 2031. HAWC is designed to address critical gaps in our understanding of the upper troposphere and lower stratosphere (UTLS), where interactions between aerosols, water vapour, ice clouds, and radiation have an important but poorly constrained influence on climate.¹ The mission combines three innovative Canadian instruments: the Aerosol Limb Imager (ALI), which provides vertically resolved measurements of aerosol and cloud properties; Spatial Heterodyne Observations of Water (SHOW), which measures UTLS water vapour with high vertical resolution; and Thin Ice Clouds and Far InfraRed Emissions (TICFIRE), which measures ice-cloud microphysical properties and far-infrared radiative emission. ALI and SHOW are both limb imaging instruments, measuring scattered sunlight, and TICFIRE is a nadir viewing instrument, imaging the mid- and far infrared emissions from the cloud tops. Together, these complementary observations will provide an unprecedented, coordinated view of aerosols, water vapour, clouds, and radiation, enabling studies of their interactions and the improvement of the representation of these processes in climate models.

1.2 Science enabled by ALI

ALI provides a critical measurement capability within HAWC because the distribution and properties of high-altitude aerosols remain poorly observed despite their important role in Earth's radiative balance, atmospheric chemistry, and cloud formation. Stratospheric and upper-tropospheric aerosol loading is highly variable and is strongly influenced by episodic events such as volcanic eruptions and increasingly important injections of wildfire smoke, creating significant uncertainty in aerosol radiative forcing and its representation in climate models. ALI uses limb-scattered sunlight to achieve the high sensitivity and fine vertical resolution needed to

Further author information: (Send correspondence to A.E.B.)

A.E.B.: E-mail: adam.bourassa@usask.ca, Telephone: 1 306 966 1418

observe these tenuous aerosol layers from the upper troposphere through the stratosphere. Its multi-spectral measurements from the visible to near-infrared provide information on both aerosol levels and particle size, while polarization measurements improve the ability to distinguish aerosols from thin ice clouds. The resulting global measurements of aerosol extinction, particle size, and vertical structure will provide an important advance over existing observations and when combined with HAWC measurements of water vapour and ice clouds will enable direct investigation of how aerosols interact with clouds and water vapour in the UTLS region. In addition to these overarching science goals of the mission, Ref. 1 notes that the primary scientific objectives of the ALI instrument are:

- Aerosol effects: To provide aerosol property measurements with excellent sensitivity to high-altitude aerosols (from forest fires, volcanic eruptions, and pollution), which have a direct impact on climate.
- Aerosols and air quality: To improve air-quality forecasting after large events, such as forest fires and volcanic eruptions, through improved knowledge of the vertical distribution of the plume.
- Aerosol data record: To extend long-term satellite records of aerosols with improved optical property characterization, critical for climate simulation.

The geophysical Level 2 data products that are anticipated from ALI are given in Table 1.

A unique strength of ALI is the combination of limb-viewing geometry, two-dimensional imaging, a wide spectral range, and polarimetric sensitivity within a single instrument. Limb viewing provides the long atmospheric path lengths required for high sensitivity to thin aerosol layers with good vertical resolution. Unlike heritage and present limb profilers, such as OSIRIS and OMPS-LP, that effectively sample the atmosphere along a narrow vertical slice, ALI simultaneously images a two-dimensional region of the atmospheric limb, providing information on horizontal structure and improving sampling of spatially heterogeneous features such as volcanic plumes, wildfire smoke, and thin clouds. The multi-spectral measurements are obtained in narrow spectral bands that span the visible and near-infrared from approximately 525 to 1560 nm, chosen to avoid interference from absorbing gases, and providing the spectral coverage needed to retrieve aerosol extinction and constrain particle size while reducing dependence on assumed aerosol microphysical properties in the retrieval algorithm.² Additionally, measurements of the polarization state of the limb signal provide a new capability for identifying and discriminating ice clouds from aerosols.

The 2022 Hunga volcanic eruption in Tonga provides a stark example of the need for ALI’s aerosol measurement capability. The recent APARC assessment³ found that although existing satellite instruments observed the transport and evolution of the Hunga aerosol plume comparatively well, estimates of aerosol extinction over the two year decay of the volcanic aerosol differed substantially, in some regions by more than a factor of two. This is much larger than typically observed and it has been recently shown by Ref. 4 that a major source of this disagreement was the dependence of limb-scatter retrievals on assumed aerosol particle size distributions, which were a poor match for the large particle sizes produced following Hunga. This uncertainty directly limits our ability to quantify aerosol optical depth, radiative forcing, and ultimately the climate impact of major volcanic and wildfire perturbations. ALI is specifically designed to address this limitation: its broad range multi-spectral measurements provide sensitivity to aerosol particle size, reducing reliance on prescribed microphysical assumptions in the extinction retrieval, while the two-dimensional limb imaging provides the spatial coverage needed to characterize rapidly evolving aerosol plumes. The Hunga eruption provided a case study that highlights both the limitations of the present observing system and the potential scientific value of ALI measurements.

2. ALI INSTRUMENT CONCEPT

2.1 Stratospheric balloon prototypes

ALI has been developed through an extensive program of stratospheric balloon prototyping that has progressively demonstrated the key measurement capabilities required for the HAWC mission. An initial prototype flown from Timmins, Canada, in 2014 demonstrated the use of an acousto-optic tunable filter (AOTF) to obtain two-dimensional multi-spectral images of the radiance of the atmospheric limb that enabled retrievals of stratospheric

Table 1. ALI science data product requirements.

Product	Precision	Range (Approximate Altitude)	Vertical Resolution
Aerosol extinction	10% goal 20% threshold	10^{-2} to 10^{-4} km^{-1} at 750 nm (5–35 km)	0.50 km
Aerosol effective radius	20% goal 40% threshold	10^{-2} to 10^{-4} km^{-1} at 750 nm (5–35 km)	0.50 km
Cloud top altitude	0.25 km	5 to 22 km	0.25 km

aerosol extinction.⁵ This first prototype was focused on showcasing the capability of the AOTF for limb imagery. An improved design of ALI added dual-polarization capability using a liquid crystal polarization rotator (LCR) in combination with the AOTF over a broad 600–1500 nm spectral range and successfully obtained the first multi-spectral polarimetric images of limb-scattered sunlight from a high-altitude balloon, with measured radiances in good agreement with pre-flight radiative-transfer and instrument-model predictions.⁶ The most recent balloon campaign in 2022 demonstrated the mature end-to-end concept, including multi-spectral and dual-polarization limb imaging, polarimetric identification of cloud-contaminated measurements, and simultaneous retrieval of aerosol extinction and particle-size parameters.⁷ Retrieved aerosol extinction and particle size under nominal observing conditions showed reasonable agreement with coincident satellite measurements. Together, these balloon campaigns provide a strong experimental validation of the ALI measurement concept and a sub-orbital heritage for its implementation on HAWC.

2.2 ALI on HAWC

While the balloon prototypes of ALI showed strong success for the measurement concept, the ATOF and LCR proved difficult for implementation on HAWC due to non-idealities in performance, including spatial and spectral ghosts, side-lobe leakage, and calibration challenges. The optical concept that is currently under development for HAWC has shifted to a more traditional approach, utilizing a mechanical filter wheel with seven narrow band interference filters to select the spectral band in collimated space following a two mirror telescope. The polarimetric capability is achieved with a divided aperture, also in collimated space following the filter wheel, that splits the optical beam into three paths that pass through polarizers oriented at 0° , 60° , and -60° with respect to the instrument frame. These three measurements allow for the derivation of the degree of linear polarization (DoLP) of the atmospheric signal.

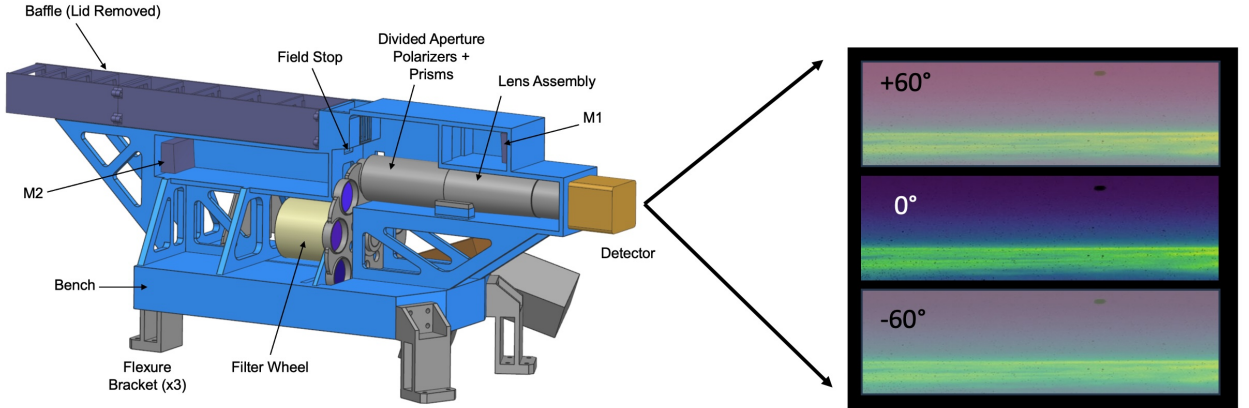


Figure 1. The ALI instrument concept for HAWC utilizes a two mirror telescope, a mechanical filter wheel for spectral band selection, a divided aperture with oriented polarizers and prisms, and focusing optics to a InGaAs focal plane array to detect three simultaneous images of the atmospheric limb radiance that can be used to derived the degree of linear polarization.

Figure 1 shows a schematic of the instrument concept with a two mirror telescope (M1 and M2), the filter wheel, and the divided aperture. It also shows the input baffle, which is a critical element for limb imaging as the bright surface of the Earth directly below the atmospheric limb is a significant source of potential out-of-field stray light. To the right of the instrument in the figure is a representation of the three images of the limb that are captured by ALI at a given narrow spectral band through the three oriented polarizers. This image is captured with a visible-light enhanced InGaAs focal plane array, nominally with 1280x1020 pixels. The images have a high aspect ratio designed to capture 45 km of tangent altitude in the vertical, roughly covering from just above the Earth's surface to the upper stratosphere, and 200 km of range in the horizontal (satellite cross-track) dimension.

The operational concept for the instrument is straightforward and simply involves successively capturing images for each spectral band as the filter wheel moves through the full set of filters. Each of the images will be binned horizontally into a set of columns, typically between 5-10, and then used to calculate vertical profiles of the radiance and the degree of linear polarization for each spectral band. The full acquisition sequence is anticipated to take between 15-30 seconds, and the horizontal binning is an important aspect of the concept to meet the signal-to-noise requirements, which range from 20 at the highest altitudes where the signal is weak to 400 at the lowest altitudes. The filters will be configured in the wheel to also allow for operational modes focused on increased spatial sampling at a limited subset of 2-3 spectral bands. The SNR requirements are a challenge due to the high dynamic range of imagery, which comes from the strong altitude dependence of the limb signal which can vary over three orders of magnitude between clouds in the upper troposphere to the weak signals in the upper stratosphere. The three simultaneous polarizations captured on the same detector adds an additional level to dynamic range as the limb signal has a strong component from Rayleigh scattering, which is highly polarized. Simulations with realistic atmospheric signals and a model of the instrument performance show that the SNR can be achieved within the nominal acquisition period except for the longest wavelengths at the highest altitudes.

The full measurement set of limb radiance profiles and DoLP for a complete set of spectral bands is then used as input to an inversion algorithm that detects the cloud tops and retrieves aerosol extinction and particle size profiles. For the central column of the image, which is aligned with the satellite orbital plane, a two-dimensional tomographic retrieval will be performed which improves the horizontal resolution of the retrieved products by using multiple acquisition sequences together to retrieve the products on a 2D grid of altitude and distance along the satellite track.

2.3 Measurement of Degree of Linear Polarization

A useful feature of the instrument concept for ALI on HAWC is the capability to measure the DoLP using the three simultaneous images passed through the three oriented polarizers. This is an improvement over the AOTF+LCR instrument concept, which only allowed for measurement of two approximately orthogonal polarization states, nominally vertical and horizontal, acquired by switching the LCR state between successive images. This switching of polarization states in time caused substantial uncertainty in the accuracy of the polarization information due to platform motion between the images, so the capability to obtain DoLP through the three simultaneous images is an important improvement to the instrument capability.

Conceptually the DoLP can be calculated by matrix inversion from the three measurements, one through each of the three polarizers in ALI, nominally orientated at 0° , 60° , and 120° . Consider the measurement for one of these polarizer angles, at an arbitrary orientation α , then the measured radiance I'_α can be written as,

$$\begin{bmatrix} I'_\alpha \\ \dots \\ \dots \\ \dots \end{bmatrix} = K_\alpha \overbrace{m_{00\alpha}}^{\mathbf{M}_{ALI\alpha}} \begin{bmatrix} 1 & \frac{m_{01\alpha}}{m_{00\alpha}} & \frac{m_{02\alpha}}{m_{00\alpha}} & \dots \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \end{bmatrix} \begin{bmatrix} I \\ Q \\ U \\ 0 \end{bmatrix} \quad (1)$$

$$I'_\alpha = K_\alpha m_{00\alpha} \left(I + Q \frac{m_{01\alpha}}{m_{00\alpha}} + U \frac{m_{02\alpha}}{m_{00\alpha}} \right) \quad (2)$$

where the Stokes vector on the right hand sides represents the state of the atmospheric radiance and is multiplied by the Mueller matrix for ALI instrument image created by the α polarizer. Note that $V=0$ is assumed for the input Stokes vector since the atmospheric signal typically does not have circularly polarized components. The α sub-script notation just notes which polarizer was used in the observation, and K is a calibration factor. Likewise, the other two polarizers - arbitrary called β and ϕ - yield,

$$I'_\beta = K_\beta m_{00\beta} \left(I + Q \frac{m_{01\beta}}{m_{00\beta}} + U \frac{m_{02\beta}}{m_{00\beta}} \right) \quad (3)$$

$$I'_\phi = K_\phi m_{00\phi} \left(I + Q \frac{m_{01\phi}}{m_{00\phi}} + U \frac{m_{02\phi}}{m_{00\phi}} \right) \quad (4)$$

The above three equations can be rearranged into a matrix form as,

$$\begin{bmatrix} I'_\alpha / K_\alpha m_{00\alpha} \\ I'_\beta / K_\beta m_{00\beta} \\ I'_\phi / K_\phi m_{00\phi} \end{bmatrix} = \begin{bmatrix} 1 & m_{01\alpha}/m_{00\alpha} & m_{02\alpha}/m_{00\alpha} \\ 1 & m_{01\beta}/m_{00\beta} & m_{02\beta}/m_{00\beta} \\ 1 & m_{01\phi}/m_{00\phi} & m_{02\phi}/m_{00\phi} \end{bmatrix} \begin{bmatrix} I \\ Q \\ U \end{bmatrix} \quad (5)$$

Given that the Mueller matrix elements and calibration factors K are known through instrument calibration activities, the Stokes vector of the atmospheric signal can be recovered through matrix inversion of the 3x3 matrix in Equation 5, and the DoLP can then be determined in the typical fashion as

$$DoLP = \frac{\sqrt{Q^2 + U^2}}{I}. \quad (6)$$

3. RETRIEVAL SIMULATIONS

3.1 Spectral and Polarimetric Information

The ALI concept was designed to include polarimetric capability in order to discriminate aerosol from cloud, and to cover a broad spectral range, extending well into the near infrared, to provide information to resolve the aerosol particle size.² However, it is well known in the remote sensing community that for nadir viewing instruments the DoLP is an important measurement not just for type discrimination but also for retrieval of aerosol properties. For example, Ref. 8 show the importance of DoLP at high accuracy for aerosol retrievals from the SPEXone multi-angle polarimeter instrument on NASA PACE. As noted above, the ALI instrument on HAWC provides a novel capability of obtaining DoLP measurements for limb imagery. The optical design approach of using the divided aperture to obtain the polarization states simultaneously allows for the DoLP to be obtained with high accuracy and here we explore the potential for using this additional useful information for the retrieval of aerosol particle size in combination with the spectral coverage.

3.2 ALI End-to-End Simulator

The utility of the spectral and polarimetric information is explored using an end-to-end simulation of the ALI measurements in combination with the retrieval algorithm. This approach is shown in Fig. 2 where an atmospheric state and orbital geometry is used as input to a radiative transfer model which calculates the signals that are incident on the instrument front end aperture. These signals are then propagated through an instrument model which accounts for the uncertainties in the measurement. The simulated measurements are then passed to the retrieval algorithm, and the output of the retrieval algorithm (aerosol extinction and particle size profiles) can be compared to the initial atmospheric state.

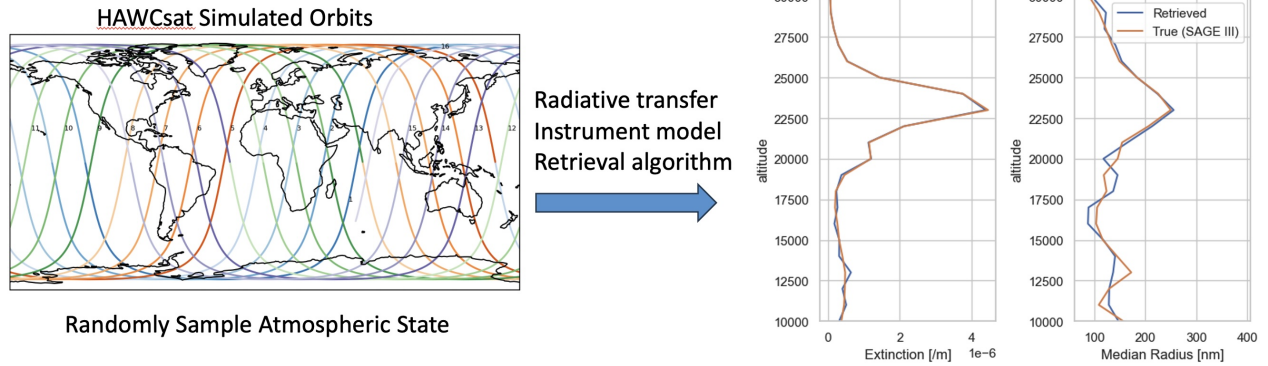


Figure 2. The ALI end-to-end simulator which takes an atmospheric state and orbital geometry, estimates the measurements, and applies the retrieval algorithm. The output can then be compared to the initial atmospheric state.

3.3 Results

To study the impact of including DoLP in the retrieval of aerosol particle size, we considered theoretical instrument configurations with two spectral ranges:

- A limited spectral range from 525-1020 nm approximately corresponding to the range of a silicon detector
- An extended spectral range from 525-1530 nm approximately corresponding to the range of a vis-enhanced InGaAs detector

and two polarimetric configurations:

- Two orthogonal polarization states (as per the heritage ALI balloon prototypes)
- Three polarization states that provide DoLP (as per the ALI on HAWC concept)

The resulting four instrument configurations were used in the end-to-end simulator for a large ensemble of atmospheric states covering quiescent and volcanically enhanced aerosol conditions, as well as for a large set of orbital geometries anticipated for HAWC. The results of the simulations are shown in Fig. 3. The left panel shows the altitude profile of median error in aerosol extinction, k , compared to the true atmospheric state, and the right panel shows the 75% error quantile. Each of the instrument configurations is shown in a different colour. Also included are the results for a simple instrument that measures only a single narrow spectral band centered at 745 nm with no polarization information. This is meant to be approximately representative of a current generation instrument like OSIRIS on Odin.

It is clear from the results that the inclusion of any spectral or polarimetric information beyond the OSIRIS-like instrument is a vast improvement. Beyond that there is a clear hierarchy to the results where, as expected, the instrument configuration with the limited spectral range and the two-state polarimetric capability performs the worst. Interestingly, extending the spectral range improves the results, but not as much as adding DoLP capability. This improvement is coming from enhanced capability for retrieval of the aerosol particle size (not shown but similar to the extinction shown here) and from the ability of the retrieval to discriminate between signal coming from aerosol scattering and that from upwelling radiation that is scattered from clouds and the Earth's surface. This is an important and novel result that shows that the measurement of DoLP provides an additional information for the retrieval of aerosol properties in the stratosphere.

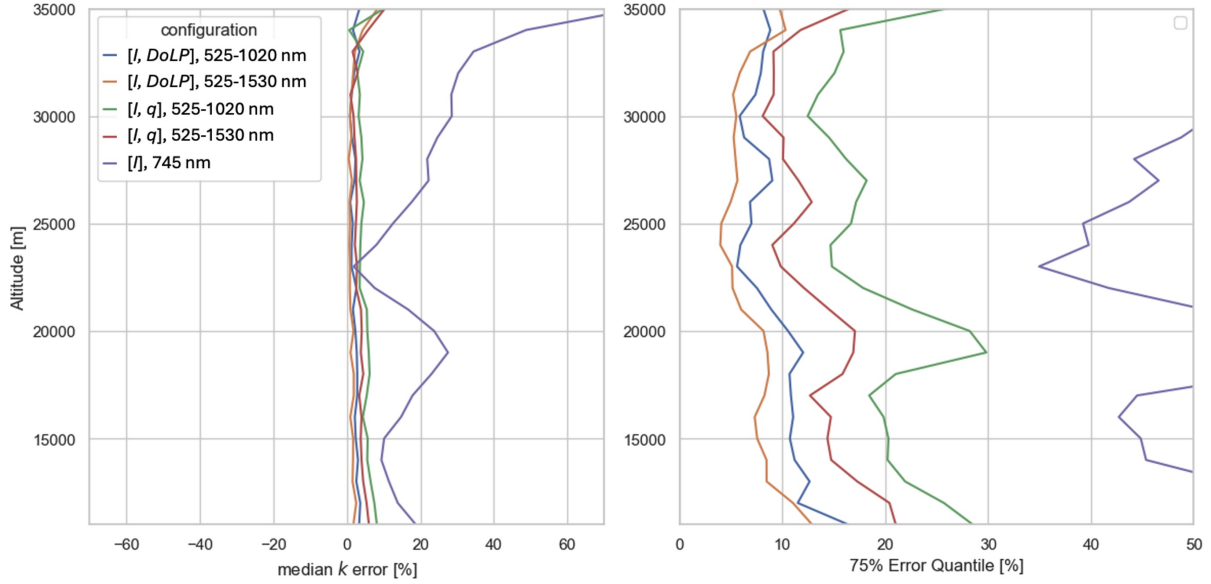


Figure 3. Results from retrievals of simulated ALI measurements with different spectral ranges and polarimetric capabilities. The left panel shows the altitude profile of median error in aerosol extinction, k , compared to the true atmospheric state and the right panel shows the 75% error quantile.

4. CONCLUSIONS

The Aerosol Limb Imager (ALI) will provide a new capability for vertically resolved measurements of aerosol and cloud properties in the upper troposphere and stratosphere as part of the HAWC mission. ALI builds on more than a decade of development and successful stratospheric balloon demonstrations of multi-spectral and polarimetric limb imaging, including retrievals of aerosol extinction and particle size and the use of polarization to identify cloud-contaminated measurements. The instrument concept currently under development for HAWC retains these key measurement capabilities while replacing the AOTF-based heritage design with a filter-wheel approach and introducing a divided-aperture polarimeter that simultaneously measures three linear polarization states. This simultaneous measurement is expected to substantially improve the accuracy of the retrieved degree of linear polarization by avoiding uncertainties associated with changes in the atmospheric scene and viewing geometry between sequential polarization measurements.

End-to-end retrieval simulations demonstrate the importance of ALI's combined spectral and polarimetric measurements. Extending the spectral coverage into the near infrared provides significant additional sensitivity to aerosol particle size, but the simulations show that accurate measurements of DoLP provide an additional and valuable constraint on the aerosol retrieval. The combination of two-dimensional limb imaging, broad visible-to-near-infrared spectral coverage, and accurate polarimetry provides a substantial improvement over that available from current-generation limb-scatter aerosol measurements. These capabilities are particularly important following major volcanic eruptions and wildfire events, when aerosol particle size and spatial structure can depart strongly from background conditions and become a dominant source of uncertainty in existing satellite aerosol products.

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REFERENCES

- [1] Langille, J., Rieger, L. A., Blanchard, Y., Blanchet, J.-P., Bourassa, A., Degenstein, D., Huang, Y., Strong, K., Walker, K., Zawada, D., Braun, S., Cole, J., Mariani, Z., McLinden, C., Paquin-Ricard, D., Sioris, C., Qu, Z., Wolde, M., Wang, X., Al-Abadleh, H. A., Ariya, P., Beltrami, H., Chang, R., Fletcher, C. G., Goldblatt, C., Grenier, P., Gyakum, J., Kushner, P., Luca, A. D., MacDougall, A. H., O'Neill, N., Pausata, F. S., Sica, R., Tan, I., Thériault, J. M., Tegtmeier, S., Toohey, M., Ward, W., and Wiacek, A., “The High-Altitude Aerosols, Water Vapor, and Clouds Mission: Concept, Scientific Objectives, and Data Products,” *Bulletin of the American Meteorological Society* **106**(11), E2358 – E2383 (2025).
- [2] Rieger, L., Bourassa, A., and Degenstein, D., “Stratospheric aerosol particle size information in odin-osiris limb scatter spectra,” *Atmospheric measurement techniques* **7**(2), 507–522 (2014).
- [3] APARC, “The Hunga Volcanic Eruption Atmospheric Impacts Report,” (2025). WCRP Report No. 10/2025.
- [4] Remai, C., Zawada, D., Bourassa, A., Dubé, K., Baron, A., Smith, K., Rieger, L., and Degenstein, D., “Stratospheric aerosol particle size explains divergent limb and solar occultation measurements after the hunga eruption,” *Geophysical Research Letters* **53**(6), e2025GL120243 (2026).
- [5] Elash, B., Bourassa, A., Loewen, P., Lloyd, N., and Degenstein, D., “The aerosol limb imager: acousto-optic imaging of limb-scattered sunlight for stratospheric aerosol profiling,” *Atmospheric Measurement Techniques* **9**(3), 1261–1277 (2016).
- [6] Kozun, M., Bourassa, A., Degenstein, D., and Loewen, P., “A multi-spectral polarimetric imager for atmospheric profiling of aerosol and thin cloud: Prototype design and sub-orbital performance,” *Review of Scientific Instruments* **91**(10) (2020).
- [7] Letros, D., Graham, L., Bourassa, A., Degenstein, D., Loewen, P., Rieger, L., and Lloyd, N., “The aerosol limb imager: multi-spectral polarimetric observations of stratospheric aerosol,” *Atmospheric Measurement Techniques* **18**(21), 6185–6210 (2025).
- [8] “Aerosol measurements by SPEXone on the NASA PACE mission: expected retrieval capabilities,” *Journal of Quantitative Spectroscopy and Radiative Transfer* **227**, 170–184 (2019).