211 DEVELOPMENT OF A MINIATURE LIDAR INSTRUMENT FOR PLUME DETECTION

Jackson Begolka*, Matthew McGill, Grant Finneman, Bolaji Oladipo, Shi Kuang

University of Iowa, Iowa City, Iowa

As the manifestations of climate change intensify, there is a growing frequency of extreme air quality events and increased strain on public health. The United States government has recognized climate change as a growing threat, with over 1 trillion USD in climate-related damages over the past seven years alone (Bhola et al. 2023). One of the many facets of climate change, wildfire smoke, is a direct threat that displaces populations and annually exposes Americans to harmful aerosols. Since the industrial revolution, air quality in the United States has improved drastically. However, there is ample room for air quality improvement. Meteorology and air quality are closely intertwined, and air quality forecasting relies on chemical transport models and numerical weather prediction models (Oladipo et al. 2024). The vertical and horizontal location of clouds and small suspended particles in the atmosphere, otherwise known as aerosols, play a crucial role in air quality, Earth's radiative budget, and climate dynamics. Aerosols vary both diurnally and seasonally with high spatial and temporal variability, making their radiative and air quality effects difficult to predict. The extent and sign of the radiative forcing effect from aerosols varies significantly based on the height at which an aerosol layer is found.

Accurate knowledge of the vertical location of clouds and aerosols has critical implications for air quality, hazard avoidance, and decision making for operations involving national security. Aerosols impact air quality and can act as tracers of events (e.g., fires or potential terrorist events), providing key information on sources and transport of potentially harmful air masses. Knowing the height of aerosols and the vertical structure of aerosol plumes is essential for predicting aerosol dispersion, transport, and visibility.

Aerosols also play a crucial role in cloud formation, and aerosol-cloud interactions (ACI) are a significant uncertainty in global radiative forcing as specified by the International Panel on Climate Change (IPCC) (Boucher and Lohmann 2013). The Twomey Effect illustrates how anthropogenic aerosols from pollution and biomass burning can act as cloud condensation nuclei, leading to enhanced cloud droplet number concentration and increased cloud albedo. ACI are complicated and can lead to both positive and negative radiative effects which are highly dependent on various atmospheric conditions.

Existing in the lower troposphere, the Planetary Boundary layer (PBL) has a typical vertical extent of a 1 to 3 km. PBL vertical extent tends to be lower over oceans and higher inland, both with strong diurnal variation. Characterized by turbulence, convective activity, and high temporal and spatial variability, the PBL and the corresponding PBL height (PBLH) play a significant role in aerosol transport and atmospheric dynamics (Palm et al. 2021). PBLH estimation is imperative to improve both air quality and climate models and it is essential to accurately measure the PBLH.

Air quality forecast models are critical for developing environmental policy and managing existing air quality issues. These models require near real-time data on the vertical distribution of aerosols and their corresponding properties. For effective forecasting, the data latency must be less than three hours (Brown et al. 2014). Delivery of accurate, low latency data and data products is an expectation of future developments in remote sensing instrumentation and is necessary to improve air quality forecasting.

Scientists, policy makers, and air quality forecast models require real-time data products that can provide accurate vertical location of clouds and aerosols. These real-time data products are paramount inputs to air quality forecast models and have critical implications for air quality, hazard avoidance, and decision making. Knowing the height of aerosols and the vertical structure of aerosol plumes is essential for predicting aerosol dispersion, transport, and visibility. Through the delivery of real-time data products that offer accurate vertical locations of clouds and aerosols, we can strengthen our

* *Corresponding author address:* Jackson Begolka, University of Iowa, Dept. of Chem. & Biochem. Engr., Iowa, IA 52245; e-mail: begolka@uiowa.edu

predictive models and put useful information into the hands of those who need it.

Passive optical and passive microwave sensors cannot provide height information accurately enough (10's m) to provide reliable aerosol and cloud detection, and distinguishing multiple layers within an atmospheric column is challenging and often impossible for passive sensors. Laser remote sensing (or lidar) is a proven method for obtaining highly accurate height registration and can distinguish cloud phase as well as differentiate clouds from aerosols. Airborne lidar, seen in Fig. 1., is also well suited for detection of background aerosols, aerosol plumes, plume boundaries, and internal structure of aerosol layers. Lidar profiling coupled with multispectral and multiangle polarimetry can provide additional information on aerosol properties.

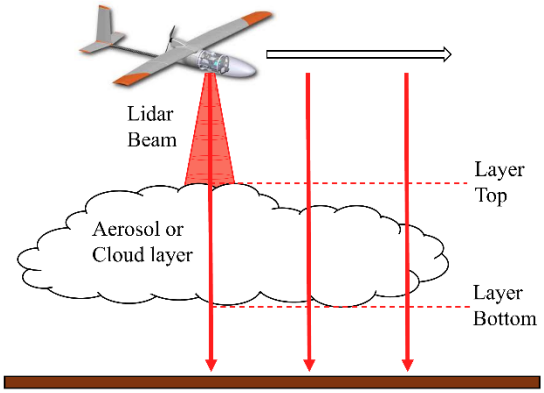


Fig. 1. Airborne lidar remote sensing concept providing layer height registration and vertical profiles of cloud-aerosol layers.

Micro-pulsed lidar technology utilizes a high repetition rate laser (on the scale of kHz), low pulse energy, and photon-counting detectors to profile cloud and aerosol scattering. With micro-pulsed lidar instruments, the retrieved photon counts are inherently lower than high pulse energy lidar instruments. By averaging over a set time, otherwise known as an average window, the solar background signal can be overcome and the signal to noise ratio enhanced.

Lidar and polarimetry are linked in cloud-aerosol studies because they provide complementary data on aerosol distributions. The capability of lidar data can be enhanced when combined with multi-spectral and multi-angle polarimetry and polarimetry offers improved characterization and monitoring of aerosol parameters, providing additional information on aerosol type, optical depth, and particle microphysics relevant to air quality (McGill et al. 2024). While lidar provides highly resolved vertical profiles, polarimetry provides scene context and enables aerosol typing through measurements of the depolarization ratio of the returned lidar signal.

Current limitations in atmospheric remote sensing include the lack of real-time data products on aerosol and cloud distributions, as well as accurate measurements of the PBLH. Air quality forecast models require real time data (< 3 hr) on the vertical and horizonal distribution of aerosols and their properties for effective forecasting.

The purpose of this project is to develop a compact and inexpensive coupled lidar-polarimeter system capable of deployment on an unmanned aerial system (UAS). The instrument will provide real-time data products on the vertical and horizontal location of clouds and aerosol plumes, along with a coarse determination of aerosol type. The miniature lidar will be capable of detecting aerosol layers with an accuracy of 10's m, and the polarized camera (polarimeter) will enable three-dimensional monitoring of aerosol plumes and adds viewing swath. Advanced machine learning algorithms will generate on-board data products that can be transported to the ground to enable real-time and informed decision making. The instrument concept will be demonstrated on aircraft before integrating the instrument design to a target UAS platform, enabling rapid cloud, aerosol, and boundary layer profiling using one or more of the instruments. Fig. 2. illustrates the instrument fleet concept and sample data products like those of the novel lidar.

The lidar optical system is designed to ensure optical beam quality and has an efficiency sufficient for accurate measurement. The transmitter and receiver take on a compact and coaxial form and utilizes a 1030 nm fiber-coupled laser. The use of a fiber laser eliminates the requirement of an open laser path and allows for further miniaturization of the instrument design. The fiber laser also acts as a field replaceable module on the lidar instrument, allowing for replacement without an entire optical system realignment. The raw photon counts are collected by a single photon counting module, which enables the use of the low-pulse energy high-repetition rate laser. All optical alignment and instrument testing is performed in the Iowa

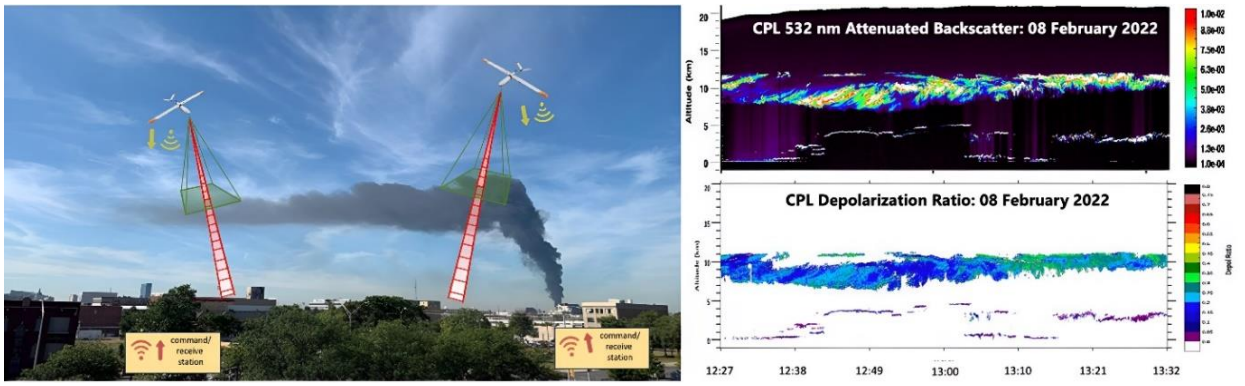


Fig. 2. Multiple miniature lidar-polarimeter platforms for remote sensing of aerosols and plume monitoring. The lidar provides vertical profiles while the polarimeter provides scene context. Instrument integration into target UAS platform and low cost enhances accessibility. Sample Cloud Physics Lidar (CPL) data products much like those of the novel lidar. Adapted from (McGill et al. 2024).

Atmospheric Sensor Development Laboratory (IASDL), shown in Fig. 3., allowing for rapid prototyping of new remote sensing technologies.



Fig. 3. The IASDL laboratory facility at the University of Iowa equipped with the Davidson 16" reflective collimator and other optical metrology equipment.

A forward model that simulates the expected instrument performance allows the IASDL team to quickly explore the design trade space and identify optimal components and averaging window for the instrument. The forward model incorporates molecular scattering and aerosol scattering based on variable aerosol and cloud layers. The laser power, pulse duration, repetition rate, receiver aperture size, detector efficiency, averaging window, and other critical parameters are variable.

To verify the instruments structural integrity and durability, a rigorous finite element analysis (FEA) is performed. The optical mounts will maintain alignment and be robust when subjected to typical loads and vibrations present during UAS operations. The instrument must also perform well when subjected to large thermal stresses and pressure changes. Based on the results of the FEA, the component layout and mounts will be redesigned. This iterative design process allows for continual development until satisfactory design is met. Through the University of Iowa, the IASDL has access to in-house vibration and thermal-vacuum testing chambers required to test instrument performance, shown in Fig. 4.



Fig. 4. The University of Iowa's in-house vibration and thermal-vacuum testing chamber

Prior to flight testing, the instrument will be assessed on ground to ensure accurate measurement and proper optical alignment. Although the lidar will be largely self-calibrating

using Rayleigh scattering, the polarimeter will require a radiometric calibration. The instrument will fly on the University of Iowa owned Operational Performance Laboratory (OPL) L-39ZA Jet, shown in Fig. 5. Upon successful operation during test flights, the instrument design will be tailored to a target UAS platform.



Fig. 5. The University of Iowa's OPL L-39ZA research aircraft.

The innovative instrument system represents a significant advancement in atmospheric remote sensing and will enhance our understanding of clouds, aerosols, and boundary layers on climate a2nd air quality. Through the delivery of real-time data products on aerosol and cloud distributions, the lidar-polarimeter system will improve forecasting of extreme air quality events, climate modeling, and decision-making processes.

REFERENCES

Bhola, V., A. Hertelendy, A. Hart, S. Bin Adnan, and G. Ciottone, 2023: Escalating costs of billion-dollar disasters in the US: Climate change necessitates disaster risk reduction. *J Clim Change Health*, **10**. doi: 10.1016/j.joclim.2022.100201.

Boucher, O., D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.-M. Kerminen, Y. Kondo, H. Liao, U., and P. R. Lohmann, S.K. Satheesh, S. Sherwood, B. Stevens and X.Y. Zhang, 2013: Clouds and Aerosols. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)].

Brown, M. E., M. L. Carroll, and V. M. Escobar, 2014: User needs and assessing the impact of low latency NASA Earth observation data availability on societal benefit. *Space Policy*, **30,** 135-137. doi: 10.1016/j.spacepol.2014.05.002.

McGill, M. J., S. D. Roberson, W. Ziegler, R. Smith, and J. E. Yorks, 2024: Real-time lidar feature detection using convolutional neural networks. *Proc Spie*, **13049**. doi: 10.1117/12.3013563.

Oladipo, B., J. Gomes, M. McGill, and P. Selmer, 2024: Leveraging Deep Learning as a New Approach to Layer Detection and Cloud-Aerosol Classification Using ICESat-2 Atmospheric Data. *Remote Sens-Basel*, **16**. doi: 10.3390/rs16132344.

Palm, S. P., P. Selmer, J. Yorks, S. Nicholls, and E. Nowottnick, 2021: Planetary Boundary Layer Height Estimates From ICESat-2 and CATS Backscatter Measurements. *Front Remote Sens*, **2**. doi: 10.3389/frsen.2021.716951.