History of Lidar Development
at the National Center for Atmospheric Research

Purpose and Scope This document traces the development of Light Detection and Ranging (Lidar) technology at the National Center for Atmospheric Research (NCAR) from its inception in 1963 to its current status. Rather than a mere catalog of instruments, this history follows the evolution of a specific mission: to transform complex laser physics into rugged, autonomous, and cost-effective tools for the meteorological community. The narrative focuses exclusively on NCAR-led research and key collaborations to solve fundamental gaps in atmospheric observation. This history serves as both a record of past achievement and a roadmap for the future.

I. The Conceptual Genesis (1960–1969)

When NCAR was established in 1960, its mission was to serve as a scientific hub—providing the university community with the large-scale observational tools and facilities necessary to understand the atmosphere. In this context, NCAR scientists viewed the newly invented laser not as a laboratory curiosity, but as a new source of electromagnetic radiation that could be used to examine the atmosphere in ways that were only beginning to be understood.

Formalizing Lidar in Meteorology: In their 1963 paper, *The Laser and its Application to Meteorology*, Goyer and Watson were among the first to hypothesize about how the technology could be used to benefit the field. They saw that by timing the backscatter of laser light, researchers could measure cloud heights, and looking further, they theorized at perhaps measuring aerosol densities. Notably, they also suggested that nascent technologies like semiconductor lasers held promise due to their small size, mechanical stability and high efficiency. They recognized that while the theoretical possibilities were vast, the path to utility would require sustained effort and concluded the paper stating: *"The reduction to practical applications is the major and more difficult step. The laser will only live up to its theoretical promises if the problems of their reduction to practice are tackled diligently in the field of meteorology".* This diligent "reduction to practice" was to become a core facet of NCAR's mission in developing observational tools [Goyer and Watson 1963].

First Experiments with Ruby Lasers: By 1968, Goyer and Watson reported on NCAR's early field work utilizing ruby lasers to map aerosol layers. At the time, technology was purely manual; researchers had to photograph oscilloscope traces using Polaroid film and manually calculate distances based on the timing of backscatter peaks. The work showed lidar could obtain nearly instantaneous profiles of aerosol layers from the ground up to roughly 30 km, demonstrating the laser was a viable tool for remote sensing of the upper atmosphere. In the same publication, they point to Schotland's [1964] first experiments to profile atmospheric water vapor using a thermally tuned ruby laser – a technique that would eventually be known as Differential Absorption Lidar (DIAL). These early attempts were technically difficult to perform, but hinted that lidar would move beyond simple cloud-height detection and one day enable profiling of atmospheric state variables [Goyer and Watson 1968].

II. Establishing the Baseline and the Synoptic Leap (1970–1979)

In the 1970s, NCAR's lidar research moved from pure experimentation to systematic observation of the stratosphere. This era established the baseline for long-term aerosol monitoring, introduced airborne platforms, and led to a critical realization about the problem of how to characterize the atmospheric effect of aerosol particles.

Ground-Based Stratospheric Mapping: Early ground-based NCAR lidar work continued to use a high-power ruby laser (up to 2 J/pulse) and a large Cassegrainian telescope. The instrument successfully mapped the stratospheric layer at approximately 20 km altitude, showing lidar could track long-term aerosol trends. There was hope that lidar could eventually help understand the large-scale atmospheric energy transfer [Schuster et al. 1970].

The Airborne Transition (1971–1973): Recognizing that ground-based systems offered only a limited view, NCAR transitioned to airborne platforms to establish a global aerosol record. A team flew a tunable organic-dye-laser on a NASA Convair 990 and collected over 15,000 profiles over the Pacific and Atlantic Oceans. The researchers addressed the unknown attenuation of the elastic backscatter lidar signal by calculating scattering ratios rather than absolute backscatter coefficients. By identifying a reference point at altitudes above 30 km—where the atmosphere was assumed to be purely molecular—they normalized their data to a model atmosphere. This approach allowed for the mathematical cancellation of two-way transmission losses, but it relied on the assumption that the high-altitude normalization point was free of aerosols and that the standard atmosphere model accurately reflected the actual air density. While an elastic backscatter lidar could synoptically map the spatial distribution of aerosols, its quantitative accuracy was limited [Fox et al. 1973].

Aerosol Characterization Realization (1972-1974): The work of Grams et al. during this period provided the empirical evidence that would eventually force a pivot in lidar research. They used the ground-based ruby lidar and aircraft sampling to investigate an aerosol layer at 13 km, discovering that the particles were highly absorbing forest fire ash. This required an imaginary refractive index nearly ten times higher than standard models assumed, demonstrating how unknown absorption could significantly bias lidar returns. A subsequent study, using a custom-built polar laser nephelometer, further highlighted the foundational difficulty of the field to derive estimates of aerosol properties. The researchers had to rely on a cascade of assumptions—applying Mie theory (which assumes spheres), assuming ground-sampled size distributions matched the air, and choosing "representative" constants for the real refractive index. Taken together, these works demonstrated that elastic backscatter lidar was a fundamentally underdetermined system, proving it alone could not provide the definitive physical data needed for climate models because shape, size, and composition remained unknown [Grams et al. 1972; Grams et al. 1974].

III. Dynamics, Safety, and the Operational Transition (1980s–2015)

By the early 1980s, understanding the limitations of elastic aerosol lidar, the focus of NCAR's lidar research shifted to the difficult task of quantitatively measuring atmospheric wind fields. This era was defined by a tension between the need for high-energy pulses and the requirement for eye-safety when operating in populated areas. Every program in this period attempted to solve this tension, leading to a series of instruments with varying degrees of operational success.

The NAILS Program (1980s)**:** The NCAR Airborne Infrared Lidar System (NAILS) utilized a pulsed CO_2 laser at 10.6 µm. This wavelength was chosen for two critical reasons: enabling advanced wind measurements and ensuring operational safety. While NAILS successfully underwent extensive ground-based testing— proving the workability of a single continuous-wave laser for both seeding and local-oscillator functions—the system faced significant internal and environmental hurdles. Technical challenges included a complex gas-handling system, high-voltage power requirements, and the necessity of cryogenic cooling for infrared detectors. Furthermore, airborne tests revealed a sensitivity to vibration, which frequently caused the laser resonator to lose its frequency lock. Although the program provided critical insights into heterodyne signal processing and established the foundation for future Doppler architectures, these persistent technical issues ultimately prevented the instrument from being deployed for operational research flights [Schwiesow 1987; Schwiesow et al. 1994; Mayor et al. 1995; Mayor et al. 1997].

The SABL Program (1990s)**:** The Scanning Aerosol Backscatter Lidar (SABL) was developed in the early to mid-1990s to visualize complex structures. It became a remote-sensing workhorse for the NCAR C-130, distinguished by its unique pod-mounted design and a 14-inch telescope built with temperature-insensitive, low-expansion materials to withstand the flight environment. While SABL provided high-resolution, 2D pictures of atmospheric structures—it was still a simple elastic backscatter lidar. This meant it was limited to identifying the spatial locations and relative concentrations of aerosol layers. Operating with a high power Nd:YAG laser with dual wavelengths of 532 nm and 1064 nm, the system also faced significant eye-safety constraints during flight operations, which limited its utility over populated areas. Following a decade of service, its final successful field project was in 2006 [Rogers et al. 1998].

The REAL Program (2000s)**:** The Raman-shifted Eye-safe Aerosol Lidar (REAL) addressed the core safety and operational limitations of previous systems by using a non-focused Stimulated Raman Scattering methane cell, to shift the laser's wavelength to 1.54 µm. This infrared region is inherently more eye-safe at high pulse energies, allowing for high-power hemispheric scanning in populated areas. While the high-power Nd:YAG pump laser and Raman cell remained technically demanding to maintain, the system's ability to create multi-dimensional maps of aerosol structures enabled unique ground-based observations [Mayor and Spuler 2004, Spuler and Mayor 2007]. To move beyond simple detection, the program integrated community-standard polarization techniques. By measuring the depolarization ratio, REAL could distinguish between spherical scatterers (liquid water) and non-spherical particles (dust or smoke), allowing researchers to coarsely identify the composition of the plumes they were tracking [Mayor et al. 2007]. The capabilities of the instrument continued to evolve under S. Mayor's leadership at California State University, Chico. Its unique scanning capability eventually allowed researchers to move beyond simple mapping toward measuring winds by tracking the movement of aerosol patterns across successive scans – a technique known as the Vector Motion Algorithm [Mayor et al. 2012].

***The LAMS Program (2010s)*:** With a pivot toward fiber-optic technology, quantitative Doppler wind measurements returned to NCAR with the development of the Laser Air Motion Sensor (LAMS). By utilizing a 1.56 μm fiber-laser architecture, LAMS not only improved portability but also removed the cryogenic needs of the NAILS era, as detectors required no liquid nitrogen to achieve high sensitivity. Initially conceptualized by NCAR to address the limitations of gust probes, prone to errors caused by fuselage-induced flow distortion [Keeler et al. 1987], the technique focused a single beam in undisturbed air roughly 15 to 30 meters ahead of the aircraft. The final version of the instrument utilized a monolithic aluminum block to house four small telescopes to resolve the full three-dimensional wind vector, a custom-built Erbium/Ytterbium fiber amplifier, and leveraged components from the telecommunications industry [Spuler et al. 2011, Spuler 2012]. While LAMS achieved high precision in measuring airspeed, its ability to resolve absolute 3D wind vectors (u, v, w) was fundamentally limited by the pointing accuracy of the Inertial Navigation Systems (INS) units of the time. Despite this limitation, researchers demonstrated that LAMS could be used to derive corrections and identify biases in flight temperature and pressure measurements [Cooper et al. 2014].

The GV-HSRL Program (2010s): Building on broader community efforts, the High Spectral Resolution Lidar (HSRL) continued a move toward quantitative observations. While standard elastic backscatter lidars produce qualitative data, the HSRL technique—pioneered by groups like the University of Wisconsin—uses a filter to separate aerosol backscatter from the predictable molecular return. By normalizing the signal against this molecular baseline, the system provides absolute units for aerosol backscatter and extinction. This specific GV-HSRL instrument, designed and built by the pioneer Wisconsin lidar group for the NCAR Gulfstream V (GV), integrated polarization capabilities to distinguish between spherical water droplets and non-spherical ice crystals [Razenkov et al. 2008]. NCAR's primary research contribution within this program addressed a specific limitation of conventional polarimetry: oriented scatterers. While the community often assumed particles were randomly oriented, aerodynamic drag can cause them to align preferentially (e.g., horizontally oriented ice plates), confounding the interpretation of standard depolarization measurements. To address this, NCAR researchers challenged the conventional assumption that measuring the full matrix requires extensive hardware redesigns. By leveraging theoretical understanding of polarization, they demonstrated that minimal, targeted modifications to the GV-HSRL—paired with sophisticated data processing based on a Mueller formalism—could enable these complex measurements without the need for a total instrument overhaul. This achievement demonstrated that standard depolarization assumptions could be affected by the presence of oriented particles. By tilting the instrument off-zenith, the team successfully identified horizontally oriented ice plates via a unique diattenuation signature and reported the first lidar detections of oriented polarization signatures in virga resulting from the flattening of raindrops during descent [Hayman et al 2012, Hayman et al. 2014].

IV. The Thermodynamic Progress: MicroPulse DIAL (2012–2022)

The modern era of NCAR lidar research marks a fundamental shift from airborne winds and mapping aerosol structures to measuring thermodynamic state variables—moisture and temperature—required to improve Numerical Weather Prediction. The transition was catalyzed by the 2009 National Research Council 'Network of Networks' study, led by NCAR's Rit Carbone, which identified a critical national gap in observing the lower atmosphere and called for a coordinated network of ground-based profiling systems [NRC. 2009]. In the years preceding this, research into high-performance water vapor DIAL capabilities helped shift NCARs attention toward water vapor as the primary variable needed to improve the initialization of weather models [Wulfmeyer 1999, Lenschow et al. 2000]. This combination set the stage for the move away from high-power research lasers toward the scalability of semiconductor-based architecture first envisioned by Goyer and Watson in 1963.

***Water Vapor*: The shift toward modern thermodynamic profiling was accelerated by a collaboration between NCAR and Montana State University. Building on the seminal work of Montana State researchers who first demonstrated that low-power semiconductor diode lasers could be used to create eye-safe, Water Vapor DIAL systems [Nehrir et al. 2011; 2012], NCAR led the effort to transform this laboratory-proven concept into a robust, field-deployable architecture. This work established the foundation for what would become the MicroPulse DIAL (MPD) program [Spuler et al. 2015]. The DIAL technique works by alternating between absorbing and non-absorbing wavelengths to provide absolute humidity profiles. Because the calculation relies on known molecular absorption lines, the system provides accurate data without the need for external calibration, offering a cost-effective path towards continuous atmospheric monitoring.. The operational performance of this architecture was confirmed in a 2016 validation study, which demonstrated that it agrees well with radiosondes and passive remote sensors while successfully detecting elevated moisture structures that passive remote sensors typically miss [Weckwerth et al. 2016].

Establishing a Network: In a move toward the nationwide scale envisioned by the 2009 "Network of Networks", NCAR collaborated with Montana State University again to construct a five-unit network of semiconductor-based lidar systems. While these units were initially designed to provide continuous water vapor profiling, they were engineered with a modular architecture. This allowed internal components to be upgraded or swapped without needing to rebuild the entire housing or telescope structure. This foresight established a scalable foundation to a standardized fleet of field instruments that could host the next major technical leap to temperature profiling.

Addition of Temperature: Expanding this architecture to include temperature profiling via Oxygen (O_2) DIAL at 770 nm was a major challenge. The underlying technique had been largely dismissed as a viable tool for decades. This skepticism was solidified by the work of Bösenberg, [1998], which concluded that the Rayleigh-Doppler effect—the spectral broadening of laser light by thermal molecular motion—rendered temperature retrievals by this method practically useless unless the resulting systematic errors could be precisely mitigated. Recognizing this, the NCAR team realized that the information required to overcome this limit was encoded in the High Spectral Resolution Lidar (HSRL) technique. This led to a strategic research shift: rather than attempting a standalone temperature retrieval, the team first focused on demonstrating a semiconductor-based HSRL, utilizing a Rubidium (Rb) vapor cell to prove the technique [Hayman and Spuler, 2017]. This research provided the framework to actually solve the DIAL equation by incorporating the HSRL-derived molecular-to-aerosol backscatter ratio. For the initial retrieval, Montana State University researchers developed a perturbative solution. By applying first- and second-order corrections to the standard DIAL equation, they proved it was possible to minimize the temperature bias caused by molecular spectral broadening [Bunn et al. 2018, Repasky et al. 2019].

***Semiconductor-Based Thermodynamic Profiling Validation*:** A milestone in this era was the construction and 2019 demonstration of the first integrated thermodynamic profiler. This proof-of-concept instrument combined water vapor DIAL, O_2 DIAL, and HSRL into a single architecture to simultaneously measure moisture, O_2 absorption, and aerosol backscatter ratio. The system utilized a potassium (K) vapor cell as a spectroscopic notch filter to separate the narrow aerosol return from the broadened molecular return, providing the critical data needed to correct O_2 spectroscopy for Rayleigh-Doppler errors. While this first-generation profiler was technically demanding and the mathematically serialized nature of the perturbative approach was highly susceptible to noise, the demonstration validated that a semiconductor-based lidar could, in principle, measure atmospheric temperature [Stillwell et al. 2020]. However, stable hardware for the O_2 DIAL architecture and signal processing capable of accurately capturing temperature structure would not come until later.

Improved diode-laser-based architecture: Building on these lessons, the MicroPulse DIAL program transitioned to a next-generation diode-laser-based architecture. This revision was specifically designed to increase technology readiness by moving from free-space optics to a robust, fiber-coupled transmitter and receiver design, fundamentally improving stability for multi-month unattended operations. It also introduced advanced numerical error estimation techniques (bootstrapping), to more accurately capture statistical uncertainty in the nonlinear DIAL equation compared to traditional linear error propagation. By maintaining independence from external calibration and models, the MPD moved closer to becoming a viable, self-contained tool for improving Numerical Weather Prediction. [Spuler et al. 2021]

V. Ongoing Work (2023 and future)

The current phase of NCAR lidar research focuses on transitioning the MicroPulse DIAL technology into a robust, scalable tool for Numerical Weather Prediction (NWP). This effort is defined by a strategic shift toward delivering advanced quantitative data, focusing on the simultaneous development of more capable, robust hardware and revolutionary data processing algorithms. By enabling deployment of these systems in autonomous networks, NCAR aims to fill the critical data gaps between twice-daily balloon launches, providing the high-frequency moisture and temperature data that is expected to finally improve short-term storm forecasting. In parallel, research has begun on evaluating the impact of these observations on weather forecasting. While an earlier Observation System Simulation Experiment (OSSE) study demonstrated that a network of continuous moisture profiles could improve predictions of severe nocturnal storm initiation timing, it also highlighted the need to move beyond idealized, single-case investigations [Kay et al. 2022].

***Framework for Advanced Retrievals*: As NCAR lidar systems moved toward low-power, semiconductor architectures, the primary hurdle shifted from hardware engineering to information extraction. To meet this, a Global Estimation retrieval method was developed. Unlike the Perturbative approach, which processes data in a sequential pipeline, this method uses a Maximum Likelihood Estimation (MLE) framework with Poisson Total Variation (PTV) to process all six MPD channels simultaneously. By treating water vapor, oxygen and aerosol wavelengths as a single coupled system, the framework accounts for their physical cross-dependencies to produce self-consistent atmospheric profiles. This represents a landmark shift in NCAR's lidar history, as it provided the first definitive demonstration that O_2 DIAL could resolve complex atmospheric temperature structures, such as inversion layers, while extending the effective retrieval range to 5 km. However, the transition to operational use remains ongoing; current systems are limited by a ~1.5 K instrument bias and the computational cost of the retrievals [Hayman et al. 2024]. Future work is focused on refining hardware stability and noise models to understand and minimize these biases for use in Numerical Weather Prediction.

***Expanding Observation Range and Resolution*: A strategic effort to overcome the peak-power limitations of semiconductor lasers by leveraging concepts similar to pulse compression in radar is being explored. This was introduced to resolve the trade-off between range and resolution – switching shot-to-shot between long-duration pulses (for high signal-noise-ratio) and short-duration pulses (for high resolution). A PTV data fusion framework merges these profiles, and for a ground-based-system like the MPD, improves near-surface coverage [Stillwell et al. 2025, Hayman et al. 2025]. Recent work has demonstrated that shorter pulses enable the MPD to resolve features—such as strong surface inversions—in the lower 500 m where the system was previously blind. While currently implemented only for water vapor channels, active research is underway to roll out shot-to-shot pulse modification across all six MPD channels to improve thermodynamic profiling below low-lying clouds. However, because DIAL techniques inherently fail within opaque clouds, this expanded range must ultimately be paired with complementary active sensors, such as Differential Absorption Radar (DAR), to achieve full-column thermodynamic profiles in all-sky conditions.

Evolution of High-Performance Mobile Architectures: Expanding on the success of the ground-based MPD, recent efforts have focused on the development of an Airborne Diode-Laser-Based (ADi) platform. Building on the foundational 780 nm Rubidium-vapor-cell HSRL design, this next-generation sensor integrates recent innovations to provide aerosol imaging with reduced cost and complexity. This work represents a significant technical leap, applying higher-average-power semiconductor-based transmitters to a compact, modular architecture designed for high-vibration and space-constrained environments. While initially conceptualized for airborne research, the ADi's core innovations are platform-agnostic:

- Moving away from high-power, high-cost legacy lasers to robust, fiber-coupled semiconductor transmitters capable of the rigorous flight environment
- Leveraging the Poisson Total Variation (PTV) framework to suppress the inherently higher noise levels in low-power laser sources
- Utilizing shot-to-shot pulse modification, to increase the signal to noise ratio required for a moving platform, while still capturing the fine-scale aerosol and cloud structure

These advancements provide a roadmap for the next generation of high-resolution remote sensors—whether deployed on ground-based mobile laboratories, diverse aircraft platforms, or in support of cross-agency field campaigns.

Conclusion

The successful transition from complex laboratory prototypes to the current generation of autonomous MicroPulse DIAL instruments confirms NCAR's progress in fulfilling the original 1963 mandate of 'reduction to practice', which is a continuous process of refinement rather than a single destination. While the technical achievement of thermodynamic profiling marks a definitive peak in NCAR's lidar history, the work is not yet complete. To achieve the necessary density for Numerical Weather Prediction, NCAR is actively engaged in commercialization efforts to scale the technology towards the hundreds of units required for a national-scale network. Simultaneously, as described in detail above, there is a focused effort to further refine hardware, software, and data processing algorithms to ensure the MicroPulse DIAL data can be successfully assimilated into the next generation of weather models. This sixty-year arc illustrates a persistent mission to bridge the gap between laser physics and meteorological utility. It ensures that as technology advances, the theoretical promises of lidar are systematically translated into the fundamental observational tools required by the atmospheric science community.

Appendix: Glossary of Terms

Aerosols: Small particles in the atmosphere deflect laser light back toward the lidar's receiver. The intensity of this return helps identify the location and relative density of clouds, dust, and smoke.

Airborne Diode-laser-based HSRL (ADi-HSRL): A current NCAR development effort aimed at replacing legacy high-power airborne systems with a modular, diode-laser-based architecture. By combining Rubidium-HSRL hardware with PTV denoising and leveraging concepts similar to pulse compression in radar, the systems could provide high-resolution 2D imaging at lower operational cost of previous technologies.

Atmospheric Energy Transfer: The process by which electromagnetic radiation (solar and terrestrial) is absorbed, scattered, or emitted by atmospheric constituents. In the context of lidar, measuring the complex refractive index of aerosols is critical because it determines the "single-scattering albedo"—the ratio of scattering to total extinction. If aerosols have a high imaginary (absorptive) component, they trap solar energy and warm the layer of the atmosphere where they reside; if they are purely scattering, they reflect energy back to space, potentially cooling the surface.

Backscatter Ratio (BSR): The ratio of total atmospheric backscatter (aerosol and molecular) to the molecular backscatter alone. Knowledge of this ratio is the "missing link" for temperature DIAL; it allows the system to determine how much of the signal is affected by Rayleigh-Doppler broadening, enabling the necessary spectroscopic corrections.

Bayesian Statistical Bias: A mathematical tendency in retrieval-based sensing where the predicted outcome is weighted toward a prior "mean state" or climatological average. This occurs in passive sensors, often resulting in the "smoothing out" of extreme atmospheric anomalies that precede severe weather.

Bootstrapping: A numerical technique used to estimate the statistical uncertainty of atmospheric retrievals. In the MPD architecture, this is implemented by splitting raw photon-counting data into two statistically independent datasets through a process called Poisson thinning. The atmospheric profile is calculated for both sets, and the variance is estimated based on the differences between them. By repeating this process for several iterations, the system generates a robust, self-contained estimate of the error.

Differential Absorption Radar (DAR): A remote sensing technique that retrieves atmospheric humidity profiles by measuring the differential attenuation of radar backscatter at two or more frequencies near a gaseous absorption line (typically the 183 GHz water vapor line). While DIAL provides high-resolution profiles in clear-air and through light haze, it is attenuated by thick clouds. In contrast, DAR is uniquely capable of penetrating clouds and precipitation, using the hydrometeors themselves as backscatter targets to measure the water vapor within and between cloud layers [Millán et al. 2024]. Because lidar and radar are sensitive to different atmospheric constituents—aerosols/molecules for lidar versus larger cloud/rain particles for radar—pairing the two techniques allows for continuous, high-resolution thermodynamic profiling regardless of cloud cover.

Differential Absorption Lidar (DIAL): A technique that uses two different laser wavelengths—one that is absorbed by a specific gas (like water vapor) and one that is not. Because it relies on known gas absorption lines, it provides absolute measurements without the need for external calibration

Diode-laser-based architecture: A design framework for lidar systems that utilizes cost-effective semiconductor (diode) lasers as the primary light source. This architecture represents a strategic transition at NCAR away from high-power, complex research lasers toward modular, low-power systems. By utilizing fiber-coupled transmitters and receivers, this architecture enables long term unattended operations and provides a scalable foundation for a standardized fleet of field instruments. Because these systems operate with lower peak power, the architecture relies on advanced signal processing to extract quantitative data while maintaining eye-safe operation in populated areas.

Diattenuation: The property of a medium or particle to attenuate light differently based on its initial polarization state. In lidar, it occurs when non-spherical particles (like ice plates or falling raindrops) have a preferred aerodynamic orientation, causing one polarization component of the laser pulse to be extinguished more than the other,

Doppler Wind Measurement: The change in the frequency of light caused by the motion of the particles it hits. In lidar, this shift is measured to determine wind speed and direction (radial velocity).

Elastic Backscatter Lidar: A basic lidar architecture that measures the intensity of laser light reflected off atmospheric molecules and aerosols at the same wavelength as the transmitted pulse. While simple to build, it suffers from the "Lidar Inversion Problem": a single measured signal depends on two unknowns—the amount of particles (backscatter) and the loss of light due to those particles (extinction). Without knowing the complex refractive index or the particle size distribution, the system cannot distinguish between a thin layer of highly reflective particles and a thick layer of weakly reflective ones, making quantitative measurements fundamentally undetermined.

Erbium/Ytterbium Fiber Amplifier: A device that increases the power of a laser signal as it travels through an optical fiber doped with the rare-earth elements Erbium and Ytterbium. Originally developed for the telecommunications industry to send data over long distances, NCAR adapted this technology to replace the bulky, high-maintenance gas and solid-state lasers of the past. These amplifiers allow for work at the more “eye-safe” 1.5 μm wavelength.

Gas Laser: A laser that uses a gas mixture (typically carbon dioxide, nitrogen, or helium) as its gain medium. Used in legacy systems like NAILS, these lasers can achieve high power but require complex gas-handling and high-voltage systems, making them difficult to maintain for autonomous field operations.

Global Estimation: A holistic data-processing framework that retrieves atmospheric properties by processing all available lidar channels simultaneously rather than in sequence. By using Maximum Likelihood Estimation (MLE) and Poisson Total Variation (PTV), this approach suppresses the noise that plagued earlier serialized retrieval methods and ensures that the retrievals are all mutually consistent across all observation channels.

Gulfstream-V High Spectral Resolution Lidar (GV-HSRL): A high-power, solid-state (Nd:YAG) airborne High Spectral Resolution Lidar developed by the University of Wisconsin and operated on the NSF/NCAR Gulfstream V (GV) aircraft. While it provides foundational 2D imaging of aerosol extinction and clouds, current efforts seek to replace this high-maintenance technology with more efficient, low-power diode-laser-based systems capable of similar 2D air-mass characterization.

High Spectral Resolution Lidar (HSRL): A specialized lidar technique that separates laser light scattered by large, slow-moving aerosols from light scattered by small, fast-moving air molecules. In thermodynamic profiling, HSRL provides the critical measurement of the aerosol-to-molecular backscatter ratio needed to correct for Rayleigh-Doppler broadening.

Inertial Navigation System (INS): A device that uses gyroscopes and accelerometers to track an aircraft’s position and orientation (pitch, roll, and heading). Precise INS data is critical for translating airborne lidar measurements into geographic wind maps.

Laser Air Motion Sensor (LAMS): A fiber-optic-based system developed in the 2010s to resolve 3D wind vectors ahead of an aircraft. It leveraged telecommunications technology to eliminate the need for cryogenic cooling and improved the accuracy of airspeed and temperature measurements

Maximum Likelihood Estimation (MLE): A statistical method used to estimate the unknown parameters of a physical system by finding the values that maximize the probability (the "likelihood") of observing the measured data. In lidar processing, MLE is used to distinguish the true laser backscatter from background noise or to estimate wind velocity from a complex Doppler spectrum. Unlike simple averaging, MLE accounts for the known statistical distribution of the noise, allowing researchers to extract accurate atmospheric profiles even when the Signal-to-Noise Ratio (SNR) is extremely low.

MicroPulse DIAL (MPD): A modern lidar architecture developed by NCAR building on Montana State University's seminal work, that uses low-power semiconductor diode lasers for continuous, autonomous profiling of water vapor and temperature. It is designed for scalability and high-density network deployment to improve weather forecasting.

Mie Theory: A complete mathematical-physical solution for the scattering of electromagnetic radiation by spherical particles of any size relative to the wavelength of light. Unlike Rayleigh scattering, which applies to particles much smaller than the wavelength, Mie theory accounts for the complex interference patterns that occur when light hits aerosols like dust, water droplets, or volcanic ash.

Mueller Formalism: A matrix-based mathematical framework used to describe how the polarization state of light changes when it interacts with an object or medium. In this system, the polarization of the laser pulse is represented by a four-element Stokes vector, and the atmospheric particles (the "targets") are represented by a 4x4 Mueller matrix. By applying this calculus to lidar returns, researchers can mathematically "decompose" the signal to identify specific physical properties of aerosols, such as their orientation or shape, without needing separate hardware for every measurement.

NCAR Airborne Infrared Lidar System (NAILS): An early 1980s airborne system utilizing a [CO_2 laser] at 10.6 μm to achieve the first quantitative Doppler wind measurements. Its complexity, including cryogenic cooling and high-voltage power needs, eventually limited its long-term operational success. The laser system also suffered from a parasitic Interferometer: an unintended optical interference caused by light reflecting between parallel surfaces inside the lidar. This created gain instability and made the system highly sensitive to the thermal expansion or contraction of the instrument chassis

Noise Model Research: To address sparse data—where signal is buried in noise—NCAR researchers developed a framework enabling the recovery of atmospheric features at unprecedented resolutions without the blurring effects of traditional averaging [Hayman et al. 2025]. Conversely, to handle high-flux scenarios like cloud returns, a new deadtime noise model was derived to correct for detector saturation. By replacing 50-year-old statistical assumptions with a model that accounts for the physical deadtime of modern sensors, the effective dynamic range is extended by over an order of magnitude [Kirchoff et al. 2025.]

NSF/NCAR Gulfstream V (GV): A high-altitude, long-range jet aircraft (also known as HIAPER) capable of flying at the lower edge of the stratosphere (up to 51,000 ft).

NSF/NCAR C-130: A rugged, four-engine turboprop aircraft used for lower-to-mid-altitude research. It is characterized by its large payload capacity and ability to fly for up to 10 hours at slow speeds.

Numerical Weather Prediction (NWP): Mathematical models used by meteorologists to simulate the atmosphere and predict the weather.

Organic Dye Laser: A laser that utilizes an organic dye (such as Rhodamine 6G) dissolved in a liquid solvent as its gain medium. Unlike fixed-wavelength solid-state lasers, these systems are "tunable" because their output wavelength can be precisely adjusted by rotating an internal diffraction grating. This flexibility allowed NCAR researchers to adjust the laser to avoid atmospheric absorption lines, while a continuous circulation pump prevented dye deterioration, enabling the high repetition rates necessary for rapid airborne data collection.

Observing System Simulation Experiment (OSSE): A modeling framework used to evaluate the potential impact of new observational data on weather forecast accuracy. In an OSSE, a "Nature Run" (a high-resolution numerical simulation) acts as the true atmosphere, from which synthetic lidar observations are sampled using a forward model. These simulated data are then assimilated into a separate forecast model. By comparing the results to a control run that lacks the new data, researchers can quantify how much a proposed lidar network would improve the prediction of specific events, such as the initiation of severe convection. A critical limitation of OSSEs is often their poor sampling statistics; because they are typically limited to a few specific weather cases, the results may not be representative of the system's performance across all climatological conditions.

Oxygen (O_2) DIAL:A specialized Differential Absorption Lidar technique used for profiling atmospheric temperature. Unlike Water Vapor DIAL, which measures a variable concentration, O_2 DIAL relies on the fact that the concentration (number density) of oxygen in the atmosphere is constant and well-known. By choosing highly temperature-sensitive absorption lines, researchers can measure the absorption of the laser signal and back out the temperature of the air molecules directly.

Passive Remote Sensors: Instruments (such as microwave radiometers or infrared satellites) that measure naturally occurring radiation emitted by the atmosphere rather than providing their own light source. Because they measure the cumulative energy along a path, they rely on Bayesian statistics and retrieval algorithms to estimate the most likely state of the atmosphere.

Poisson Total Variation (PTV): A revolutionary signal processing framework used to handle sparse photon-counting data. It allows for the recovery of atmospheric features at high resolution without traditional "blurring" or averaging, even when signal levels are extremely low. The processing framework aims to minimize a combination of total variation (difference between pixels of estimated variables) and error in fit noisy observations (assessed based on a Maximum Likelihood framework). Poisson refers to the original assumed noise model of observations when the algorithm was developed (though this is not always used now) and Total Variation refers to the penalty applied to the objective function to avoid over-response to noise in signal estimates.

Polar Laser Nephelometer: An instrument that measures the intensity of light scattered from a collimated beam as a function of the scattering angle. In the NCAR the system utilized an argon-ion gas laser as the source, providing high-intensity, monochromatic light at 514.5 nm. By measuring these angular patterns alongside particle size distributions, researchers used Mie theory to derive the complex refractive index of aerosols. This hardware-driven approach provided the empirical evidence that airborne soil particles had an imaginary (absorptive) component, a discovery that fundamentally changed how lidar data was interpreted.

Potassium (K), or Rubidium (Rb) Vapor Cell: A small glass container filled with Potassium or Rubidium vapor used as a spectroscopic filter. In HSRL systems, it acts as a "notch filter" to block out specific parts of the laser return, allowing for high-accuracy temperature profiling.

Perturbative Temperature Retrieval: A serialized processing method used to solve the two-component atmosphere DIAL equation by applying first- and second-order corrections to minimize biases caused by Rayleigh-Doppler broadening. In this framework, water vapor and aerosol backscatter data are processed first using conventional techniques and then supplied as fixed constants to the temperature retrieval. While this method proved that semiconductor-based lidars could, in principle, measure temperature, its serialized nature makes it highly susceptible to noise compounding and limits its ability to resolve fine-scale structures like temperature inversions. At NCAR, this method has been superseded by the Global Estimation framework.

Radiosondes: A battery-powered instrument package carried into the atmosphere by a weather balloon that measures vertical profiles of pressure, temperature, and humidity. While highly accurate, they are typically launched only twice daily from fixed locations, leaving significant "data gaps" in the high-frequency timing needed for modern storm forecasting

Raman-shifted Eye-safe Aerosol Lidar (REAL): A ground-based system that achieved eye-safety by shifting laser light to 1.54 μm using Stimulated Raman Scattering. It enabled hemispheric scanning in populated areas and could distinguish between dust, smoke, and liquid water using polarization.

Rayleigh-Doppler Broadening: The spectral broadening of returned laser light caused by the random thermal motion of air molecules. This broadening introduces significant errors in temperature DIAL retrievals if not explicitly measured (e.g., via HSRL)..

Refractive Index (Complex): A dimensionless number that describes how light propagates through a medium or particle, expressed as $m = n - ik$. The real part (n) represents the degree of refraction (bending of light) and contributes to the backscattering strength. The imaginary part (k) represents the absorption coefficient, or how much light energy is lost as it passes through the particle. In lidar meteorology, knowing both terms is essential for distinguishing between different aerosol types, such as highly reflective ice crystals versus highly absorbing volcanic ash/soot.

Scanning Aerosol Backscatter Lidar (SABL): A 1990s-era airborne workhorse that provided high-resolution 2D imaging of atmospheric structures. While limited by eye-safety constraints and its qualitative "elastic" nature, it featured a unique temperature-insensitive pod design for flight operations.

Semiconductor (Diode) Laser: A laser that uses a p-n junction to convert electrical current directly into light. These are the core of the modern MPD program because they are highly efficient, mechanically stable, and mass-produced, enabling the low-cost scalability required for a national observation network.

Stimulated Raman Scattering (SRS): A non-linear optical process used to change a laser's wavelength. In the REAL program, a methane cell, also referred to as a “Raman cell”, used SRS to shift the 1064 nm near-infrared light from a fundamental Nd:YAG laser into the more eye-safe 1543 nm infrared region.

State Variables: The fundamental physical properties that define the state of the atmosphere, specifically temperature, pressure, and moisture (humidity).

Solid-State Laser: A laser that uses a solid gain medium, such as a crystal or glass doped with rare earth elements (e.g., the Ruby laser or Nd:YAG). These are often used for high peak power applications but can be difficult to cool as they have poor wall-plug efficiency, requiring high electrical input for modest optical output. Crucially, maintaining the single-frequency stability required for precise lidar measurements is expensive and technically challenging in these systems.

Undetermined System: A mathematical state where the number of unknown variables exceeds the number of independent measurements (equations) available, making it impossible to calculate a unique solution. In lidar history, simple elastic backscatter systems are inherently undetermined because a single backscattered signal is influenced by both particle concentration and particle absorption/extinction. Without auxiliary data—such as that provided by the polar nephelometer—researchers cannot solve for the atmospheric state without making significant, often inaccurate, assumptions about the complex refractive index.

Water Vapor (WV) DIAL: A technique that alternates between a wavelength absorbed by water vapor and a reference wavelength that is not. By comparing the two returns, the system calculates absolute humidity profiles without needing external calibration. This provides direct, range-resolved moisture data that identifies precursors to severe weather often missed by passive sensors. **High-Performance WV DIAL** requires high-power, tunable laser systems such as Alexandrite or Titanium:Sapphire (Ti:Sapphire). While these complex instruments—notably utilized at NCAR by V. Wulfmeyer —demonstrated the ability to resolve turbulent processes in the lower atmosphere, they were primarily research-grade tools rather than the scalable, autonomous systems seen today.

Volume Imaging Lidar: A lidar system, capable of performing rapid, multi-dimensional scans (often hemispheric) to create 3D "data cubes" of atmospheric structures. This allows researchers to visualize the evolution and movement of the boundary layer rather than seeing only a single vertical or horizontal slice.

Vector Motion Algorithm: A computational method used to derive wind fields by tracking the spatial displacement of atmospheric features (such as aerosol plumes) across successive lidar scans. Unlike Doppler lidar, which measures wind based on frequency shifts, this "feature-tracking" approach relies on high-resolution volume imaging to determine velocity and direction.

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