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MicroPulse DIAL (MPD) for Thermodynamic Profiling of the Lower Troposphere

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Abstract: The MicroPulse DIAL (MPD) was developed to address a long-standing observational gap in atmospheric science, specifically focusing on tropospheric thermodynamic profiling to enable large-scale national networks. This extended abstract provides an overview of the development path and the latest lidar architecture employed in the MPD.

1. Introduction

The MicroPulse DIAL (MPD) was developed to bridge an observational gap in atmospheric science, to enhance the prediction of mesoscale severe weather events. Accurate lower tropospheric profiles of water vapor and temperature are imperative for this purpose, requiring relatively high temporal (<60 min) and vertical resolutions (<300 m), coupled with horizontal scales/spacings of approximately 200 km [1,2,3,4]. Although Raman lidars offer the requisite range and temporal measurements, their feasibility for large-scale national networks is hampered by their inherent costliness in construction, operation, and maintenance. Thus, the pursuit to develop a new profiling technology capable of supporting such a network has been the primary scientific motivation. Over the past decade, our efforts have been directed towards crafting a novel class of active remote sensors to potentially enable more cost-effective thermodynamic profiling.

2. History of Development

In pursuit of a lidar scalable to a national network, our focus has shifted towards leveraging a semiconductor laser-based architecture. This approach offers key advantages such as reduced costs, maintenance, and extended lifespan, while simplifying the attainment of eye-safety classification. However, state-of-the-art semiconductor lasers yield output powers far below those of solid-state lasers used in Raman lidar. To achieve comparable performance, we turn to lidar techniques relying on elastic scattering, notably differential absorption lidar (DIAL), which is significantly more efficient than Raman scattering. Leveraging elastic scatter as a distributed backscatter reflector enables operation at substantially lower power than Raman lidar systems, facilitating the use of semiconductor lasers. The narrowband DIAL technique offers the added advantage of self-calibration without the need for ancillary observations, albeit requiring a frequency-agile single-frequency laser source and rough estimates of atmospheric temperature and pressure. Additional architectural design requirements include the use of spectral filter techniques for achieving ultra-narrowband receivers.

Following the seminal research in diode laser based water vapor DIAL at Montana State University [5], a field prototype was developed collaboratively at NCAR. The first field project with this instrument was in the summer of 2014 in Colorado, USA. Initially, the prototype was referred to as water vapor DIAL, though this term technically denotes a technique rather than a specific instrument name. It was later renamed MicroPulse DIAL (MPD for short). This initial demonstration showcased continuous, high vertical resolution water vapor measurements during a two-month field campaign [6].

A subsequent field project occurred in the summer of 2015 in Kansas, USA, providing examples of the instrument's capability to accurately measure rapidly changing water vapor, particularly in elevated layers, without requiring external calibration. During this project, the instrument was co-located with two passive sensors: an infrared and a microwave radiometer. The passive instruments failed to resolve lofted (mid-level) water vapor, likely due to their coarse vertical resolution or nature of the retrieval, which steers them toward climatological means. As summarized in the paper, water vapor measurements using a low-power semiconductor-laser-based lidar proved to be a useful tool [7]. However, the need for thermodynamic profiling became apparent, prompting consideration of temperature measurement methods.

The lidar community had explored the use of the DIAL technique to measure temperature in the 1990s, focusing on temperature-sensitive oxygen lines. This research, led by Bösenberg [8,9], encountered a significant challenge stemming from Rayleigh-Doppler effects, leading to temperature uncertainties exceeding 10K. However, achieving temperature uncertainties of less than 3K is essential to enhance Numerical Weather Prediction accuracy as defined by the World Meteorological Organization.

The issue Bösenberg identified stems from the optical properties of the atmosphere. At these wavelengths, light is elastically scattered by aerosols and molecules in distinct ways. Aerosols, scatter laser light back with minimal alteration. Conversely, low mass air molecules, operating within the Rayleigh regime, exhibit random thermal motion, moving at around 300 m/s. Consequently, light scattered from these molecules experiences significant Doppler broadening. In the context of DIAL, accurately measuring absorption on the return path necessitates understanding the contribution of Doppler-broadened Rayleigh scattering, particularly crucial for narrow absorption features like oxygen.

We thought that perhaps this problem could be addressed by employing another technique known as High Spectral Resolution Lidar (HSRL). HSRL involves placing a narrow absorber, typically an atomic vapor filter, in the receiver and splitting the light into two channels. In one channel, the total signal is measured, while in the other, only the contribution from the molecular signal is captured. This approach enables a direct measurement of the molecular-to-aerosol ratio, which was the missing piece in Bösenberg's work. Due to the flexibility of the semiconductor-based lidar architecture, it seemed feasible to integrate these two methods. To illustrate this concept as a pathway to temperature measurement, in 2017, we developed a next-generation instrument combining water vapor DIAL with an HSRL [10].

After successfully demonstrating the feasibility of a combined system, our focus shifted back to researching temperature profiling. The concept for oxygen DIAL is analogous to that used for water vapor. We transmit two additional wavelengths, bringing the total to four. However, in this case, the amount of oxygen in the atmosphere is theoretically known, and we are measuring the absorption coefficient, which is temperature-sensitive for the chosen O2 absorption line. The offline wavelength was selected to coincide with a Potassium absorption line utilized in the receiver of our HSRL channel. Temperature retrieval is significantly more complex than water vapor absorption, and the initial algorithms were developed by our long-time collaborators at Montana State University [11,12].

In the subsequent phase of development, we embarked on constructing a prototype of the thermodynamic instrument. Essentially, we aimed to build a lidar system capable of conducting three measurements within a single framework: WV-DIAL, HSRL, and O2-DIAL. The first demonstration of this technique took place in 2019, coinciding with an engineering test of a five-unit network of MicroPulse DIAL instruments. Notably, one of the instruments within the network featured the prototype temperature capability for this test [13]. It was evident that the combined system performed well at measuring WV when compared to more mature measurements. The MPD not only provided similar WV profiles to the much more powerful Raman lidar but also offered a completely independent measurement. While the Raman lidar relies on radiosonde calibration (to remove functional dependencies on optical alignment and atmospheric propagation of relatively broadly spaced wavelengths), the narrowband DIAL technique is self-calibrating by design. During this test, we obtained a limited amount of temperature data, totaling just over 60 hours. While the data showed promising results, with 69% of the measurements falling within the 3K threshold, it became apparent that improvements were necessary. We recognized the need to enhance the system hardware for more robust field operation and to investigate alternative temperature retrieval algorithms.

3. Latest Thermodynamic Results

Using the redesigned architecture [14], the first thermodynamic profiling data collected during a scientific field campaign occurred in summer 2023 in a remote area of Nevada, USA. Throughout the project, over 100 radiosondes were released, with all but one of these sondes launched during daylight hours. The temperature data, processed using the original temperature retrieval algorithm and 60-minute averaging, indicated that the technique was just reaching the threshold goal of 3K uncertainty.

However, concurrently with advances in instrument hardware, we had been developing advanced processing techniques for temperature data. The new method employs a global retrieval approach that considers channel cross-dependencies, maximizes available information content, and minimizes noise. The global estimation of thermodynamic variables not only provides significantly more data but also yields lower data product errors compared to the standard method. The new method demonstrates the capability to track with radiosondes up to 5 km, and excels in capturing temperature inversions in the atmosphere, a challenge for standard methods due to limitations in maximum range and noise [15].

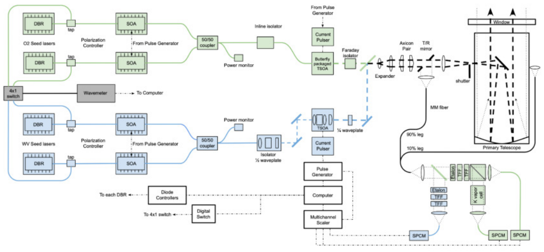

Figure 1: Schematic diagram of the MPD. A fiber-coupled lidar transmitter and shared transmit/received path are utilized. Green-shaded components are for temperature profiling, and blue-shaded components are for water vapor DIAL

4. Latest Lidar Architecture

Following the last field project, the thermodynamic profiling architecture was integrated into all five of our MicroPulse DIAL instruments. Figure 1 illustrates a schematic layout of the latest design. The transmitter is a variation of a Master Oscillator Power Amplifier (MOPA) configuration. The master oscillator seed lasers are fiber-coupled Distributed Bragg reflector (DBR). Separate lasers are used to provide the online and offline resonance frequencies for water vapor absorption. Pulsed Semiconductor Optical Amplifiers (SOAs) serve as multifunction amplifiers and switches. As these SOAs are pulsed, the seed lasers are either amplified or absorbed, with the blocking properties of SOAs providing off-channel isolation better than 40 dB. The pulsed online and offline seed lasers are interleaved in time, on a pulse-by-pulse basis, and combined into a single fiber using a 50/50 fiber coupler. The final power amplifier stage employs a tapered amplifier, which starts with a waveguide, like the SOA, and expands in one dimension to prevent catastrophic optical damage. In pulsed, current overdriven mode, peak power of up to 10W can be achieved. The components required for temperature measurements are highlighted in green in the schematic, mirroring the WV transmitter architecture while incorporating frequencies for molecular oxygen (O2) absorption.

To reduce background noise, several techniques are employed, including a narrow field of view and a two-stage ultra-narrow passband in the receiver utilizing thin film filters and etalons, achieving a 20 pm effective bandpass. Additionally, the backscatter ratio must be known to correct the oxygen spectroscopy, leading to the inclusion of an HSRL channel in the receiver, utilizing a K-vapor cell to provide this data.

Recently, we incorporated a fiber-coupled tapered amplifier on the O2 transmitter side, marking the first time the entire transmitter has been fiber-coupled, enhancing design robustness. Additionally, the smaller collimated beam from the package allows for the inclusion of a Faraday isolator with relatively low loss, providing improved protection from feedback that could degrade spectral purity, a critical factor for DIAL applications. The instrument now utilizes polarization-maintaining (PM) seed lasers, PM SOAs, and subsequent PM fiber for both water vapor and O2 transmitters.

5. Conclusion

The MicroPulse DIAL (MPD) was developed to address a longstanding observational gap in atmospheric science requiring accurate tropospheric thermodynamic profiling essential for improving weather prediction and understanding atmospheric processes. Through continuous development efforts, the MPD has integrated state-of-the-art semiconductor-based lidar architecture, including fiber-coupled components, ensuring robustness and reliability in field operations.. The culmination of these advancements positions the MPD as a valuable tool for atmospheric research, offering independent and reliable measurements for verification, validation, and data assimilation in numerical weather prediction models.

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