Simultaneous Measurement of Water Vapor, Temperature and Aerosol Backscatter with Diode-Laser-Based Lidar

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Abstract: The MicroPulse DIAL (MPD) system utilizes a diode-laser-based architecture to operate at two near-infrared wavelength regions, facilitating water vapor DIAL, High-Spectral-Resolution Lidar (HSRL), and oxygen DIAL techniques at. The instrument provides simultaneous measurement of absolute humidity, backscatter coefficient, and temperature at resolutions of 5 minutes and 37.5 meters with a typical range from 300 m to 5 km. This self-contained instrument provides standalone observations of atmospheric thermodynamics, eliminating the need for external calibration, ancillary data, or assumptions. Consequently, the MPD stands as one of the few fully self-sufficient thermodynamic profilers in existence. A novel statistical signal processing approach has emerged as pivotal in enhancing the accuracy of data products from the MPD. This processing capability facilitates comprehensive accounting for interdependencies within instrument data products while effectively mitigating the impact of shot noise through denoising techniques. This presentation will outline the new signal processing approach and show select results demonstrating its efficacy.

1. Introduction

The MicroPulse DIAL uses a diode-laser-based transmitter to enable low-maintenance, low-power, eye-safe (class 1M) observations of thermodynamic profiles. It consists of three lidar architectures consolidated into a single instrument operating at two near IR wavelengths. Operation at 828 nm enables the water vapor (WV) DIAL architecture which is primarily sensitive to absolute humidity while the 770 nm wavelengths are leveraged for HSRL (with potassium vapor cell filter) and an oxygen DIAL – for measuring aerosol backscatter coefficient and temperature, respectively. In total, the MPD represents a complete thermodynamic profiler, obtaining vertically resolved profiles of aerosol backscatter coefficient, absolute humidity and temperature without use of any external information for calibration or processing. Where many instruments leverage assumptions, priors (e.g. Bayesian and machine learning methods) or calibrations from external sources, the MPD represents a fundamental shift away from intermingling of data, models and assumptions that can result unaccounted for correlations in errors across observations and models. Instead MPD produces a stand-alone product.

While WV DIAL and HSRL techniques have a considerable legacy in lidar research, the oxygen DIAL technique has virtually no historical use. The technique was proposed long ago, and analysis performed in the 1990s showed that without correction for Rayleigh-Doppler effects, errors in temperature estimates would exceed 10s of K. As a result, the technique was largely dismissed as not being viable.

At the National Science Foundation National Center for Atmospheric Research (NSF NCAR), we have devised a scheme for directly measuring the Rayleigh-Doppler effect and accounting for it by using the integrated HSRL measurements in the instrument. However, accounting for this effect requires a deviation from the standard DIAL equation and new processing approaches would need to be developed.

The initial processing scheme for MPD leveraged a serialized process where HSRL and WV DIAL were processed independently using the standard approaches. The results of those estimates were supplied to an oxygen DIAL processing technique based on a perturbative approach [1, 2]. However there are shortcomings with this approach. First, even though the estimator eventually supplies a temperature profile, the temperature must be assumed for processing WV and HSRL data. As a result, the products are not entirely self-consistent. Second, the HSRL and WV DIAL products are noisy and fed into a processing routine which is highly noise sensitive. This results in noisy temperature profiles and limits the time and rage resolution of the product.

The existence of noisy temperature profiles appears to be a particular challenge in interpreting temperature data where variations in features are small and infrequent. It is nearly impossible to know if a wiggle is indicative of an actual feature (such as an inversion layer) or just random variation.

Poisson total variation (PTV) is a regularized maximum likelihood estimation technique that has been shown to improve HSRL [3] and WV DIAL retrievals [4]. This estimation approach provides denoised data products and leverages a forward modeling approach. This addresses the two key drawbacks of the standard approach for estimating temperature from the MPD. PTV is able to suppress noise in the temperature, absolute humidity and backscatter retrievals and minimize noise in the data products. It is also able to account for cross dependencies in the three lidar architectures and solve for all three data products simultaneously, thus ensuring consistency across all data products.

We have now developed a PTV implementation for processing MPD observations and providing full thermodynamic profiling products [5]. Those retrievals have been validated against 119 radiosondes at the M2HATS field campaign in summer 2023 [6].

2. MicroPulse DIAL

The MicroPulse DIAL architecture consists of a Master Oscillator Power Amplifier (MOPA) transmitter where narrow linewidth seed lasers undergo two stages of amplification. The water vapor DIAL part of the instrument has been described in detail in [7] which was duplicated at additional wavelengths to demonstrate the HSRL concept [8] and then combined HSRL/oxygen DIAL [9].

The instrument broadly operates at two wavelengths where each wavelength of operation actually consists of two closely spaced frequencies corresponding to online and offline frequencies for the DIAL species of interest (WV at 828 nm and oxygen at 770 nm). The WV system utilizes only one detector, while the 770 nm receiver consists of a combined detector (similar to the single 828 system) and a molecular detector where a potassium vapor cell is used to block aerosol returns at the 770 nm offline frequency. As a result, the transmitter consists of four different laser frequencies (two at each wavelength), three detectors and a total of six observations. Fig 1 depicts this transmitter/receiver configuration.

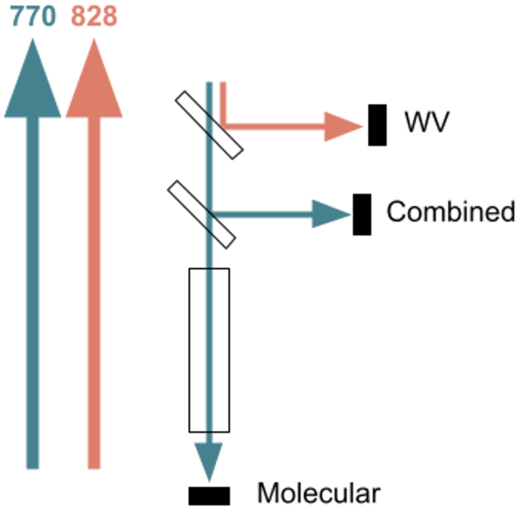

Figure 1. Simplified MPD Architecture

3. Poisson Total Variation

Poisson Total Variation (PTV) is a regularized maximum likelihood framework whereby estimated products are forward modeled onto the noisy observations. The products are iteratively updated to obtain a best fit to the observations. The quality of fit is determined by the noise model of the observations. For photon counting lidar we assume a Poisson noise model. The loss function is the negative log-likelihood of the noise model and therefore given by

$$\mathcal{L}(x) = \sum_{n=0}^{N} f_n(x) - y_n \ln f_n(x) \tag{1}$$

where x is the estimated state variable (temperature, backscatter, and water vapor) $f_n(x)$ is the function that forward models the state variable to the describe the observations on the *nth* channel, and y_n are the observed photon counts on the *nth* channel. The specific formulation of the instrument forward model for the MPD is described in detail in [5].

In addition, total variation regularization is applied to the overall cost function to penalize changes in the estimated state variables. The amount of regularization is controlled by a constant λ_i (corresponding to estimated variable x_i) such that larger values impose a greater penalty for changes in the estimated variable. The estimated thermodynamic state is then obtained by minimizing the cost function which consists of both fit and regularization terms.

$$\hat{x} = argmin\, \mathcal{L}(x) + \sum_{i=1}^{I} \lambda_i ||x_i||_{TV} \tag{2}$$

4. Results

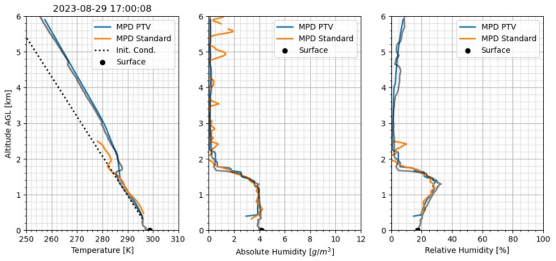

Figure 2. Retrieved thermodynamic variables

An example of MPD thermodynamic retrievals processed at 5 minute and 37.5 m resolution from 300 m to 6 km are shown with comparison to a radiosonde in Fig. 2. Radiosonde data is used for comparison only; at no time is it used for the retrievals The radiosonde measurement is the gray line. The standard MPD processing approach is shown in orange and the PTV processing approach described here is shown in blue. Note that the PTV retrieval is able to extend the maximum altitude above than the standard method and random fluctuations are largely suppressed by the technique.

The thermodynamic variables in Fig. 2 are obtained by fitting them to the observed photon counts. The fits obtained from the state variables shown in Fig. 2 are shown in Fig. 3 for all six observation channels.

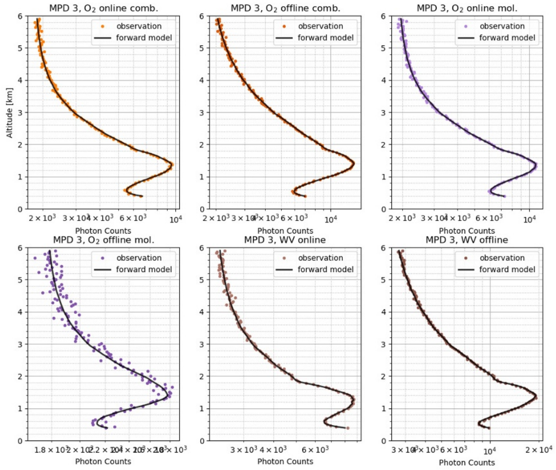

Figure 3. Forward model fits to MPD

Because PTV leverages a forward modeling approach, it ensures that any data product we obtain through the technique is self-consistent with the observations and therefore the fits align well with the observation (without residual noise). This is not typically true with standard lidar inversions where signal processing such as smoothing can result in data products that are not consistent with the observed raw signals.

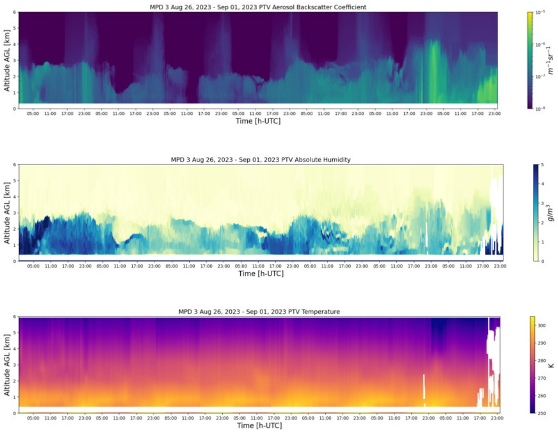

Figure 4. Time series of retrieved variables

An example time series of all three MPD data products are shown for a one week period in Fig 4. The top figure shows the aerosol backscatter coefficient, middle – absolute humidity and bottom – temperature. Note that the diurnal banding in backscatter coefficient is a product of solar background raising the noise floor and increasing the minimum detectable backscatter coefficient.

The MPD is able to profile throughout the day over long durations. It is, however, limited by the presence of clouds where the noise model is not Poisson (due to non-ideal detector effects) and the backscatter structure is changing much faster than the instrument integration time. Overall PTV tends to have lower data availability than the standard processing approach below 3 km due to its sensitivity to the assumed noise model. However it also provides lower error retrievals with improved ability to separate structure from noise. A more comprehensive analysis of the MPD temperature retrievals is provided in [5].

Additional hardware improvements aimed at reducing biases and integration of a noise model accounting for detector dead time are currently underway and the results of those efforts will be discussed.

5. Conclusion

By integrating HSRL, WV DIAL, and oxygen DIAL, the MicroPulse DIAL acquires data for deriving thermodynamic profiles without reliance on external calibration, assumptions, or supplementary data. Utilizing the PTV technique to process this data reveals the capability of producing accurate denoised profiles. Furthermore, our findings underscore the feasibility of utilizing oxygen DIAL for temperature profiling, which is particularly advantageous for low-power diode-laser-based systems. Ultimately, this study highlights the impact of advancements in signal processing, expanding measurement capabilities and enabling techniques previously deemed unattainable.

6. References

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