Extending the Observational Range of the MicroPulse DIAL (MPD) Instrument Through Shot-To-Shot Modification of Laser Pulse Characteristics

Robert A. Stillwell[(a)], Adam Karboski[(a)], Matthew Hayman[(a)], and Scott M. Spuler[(a)]
(a) NSF National Center for Atmospheric Research, Earth Observing Laboratory, Boulder, CO, USA
E-mail: stillwel@ucar.edu

Abstract: An experimental timing system is described that modifies the laser pulse characteristics shot-to-shot for a semiconductor-laser-based lidar system. An example is explored where the modification of laser pulse length allows for the system to reduce its minimum observable range by alternating relatively narrow pulses (on the order of 10-200 ns) with relatively wide laser pulses (on the order of 1 μs) to maintain sufficient average power to see at long ranges. This effectively creates a low- and high-gain receiver configuration with identical optical alignment properties without adding any optical components.

1. Introduction

Traditional lidar measurements have heavily leveraged high-power lasers to compensate for weak return signals from the atmosphere. While signal-to-noise ratios scale with output laser power, raw performance of measurements often comes at the expense of system complexity, reliability, and higher procurement and operating costs. Conversely, low-power lasers leveraging semi-conductors and/or fiber-coupled optical components can be made reliable, simple, and are relatively inexpensive. This class of lidar might be ignored based on the assumption that measurement performance would be insufficient, yet it depends on the measurement requirements.

Historically, lidar designers have largely chosen to deal with the complexity, reliability, and cost issues related to high-power lasers seeking high quality “hero measurements”. However, there is a major push from atmospheric scientists to consider a new set of design criteria. A 2009 report from the National Research Council [1] and subsequent reports [2,3] have proposed that increased scientific utility would result not from single measurements but broadly distributed network measurements.

The need for broadly deployed lidar systems – perhaps several hundred for an area the size of the continental United States – places more emphasis on the design criteria of reliability, simplicity, lack of ancillary calibration, and cost. This design space favors low-power lasers significantly. For this reason, the MicroPulse Differential Absorption Lidar (MPD) was developed. The lidar architecture is based on low-power semiconductor lasers and has been successfully used to measure water vapor, temperature, and calibrated aerosol backscatter via differential absorption lidar (DIAL) and high spectral resolution lidar (HSRL) techniques.

Designers of lidar systems that leverage low peak-power lasers (e.g., semiconductor lasers) are presented with a tradeoff between pulse length and observational range. With limited peak power, longer pulses emit greater total power per pulse, which allows for increased maximum observational range. However, with longer pulses, the systems’ minimum range is necessarily increased – limiting the ability to measure atmospheric conditions near the earth’s surface in vertical profiling applications. This is because the pulse must first completely exit the lidar system; for a DIAL application, a pair of measurements in range is required. Furthermore, longer pulses tend to smooth observed atmospheric features.

While theoretically simple to pose, selecting a pulse length for low peak-power lasers is not straightforward to address. This paper introduces a system that allows the pulse characteristics of the lidar system to change from shot to shot, which allows for greater flexibility to address both near and far ranges of the measurement.

2. Pulse Compression

The problem of defining a pulse length is not unique to lidar systems. Some modern radar systems have a similar tradeoff related to pulse length. However, a method called "pulse compression" allows for the emission of reasonably long radar pulses while maintaining high range resolution [4]. The concept is to impart a unique pattern into a pulsed signal that can be used to identify from which portion of the pulse the return signal originates. For modern radar, this typically involves flipping the phase of the outgoing waveform and subdividing the outgoing pulse into "keys". Theoretically, wave amplitude and frequency can also be altered. With these "keys", there are known code sets, such as Barker Codes, that have advantageous autocorrelation properties. One simple code set is +1,+1,-1; if one considers amplitude modulation, this is just a longer pulse and a shorter pulse offset in time.

3. Example of Pulse Modification

For MPD's water vapor measurement, described by [5,6,7], pulse widths on the order of 650 ns to 1 μs are typically used. For pulses of length 1 μs, the minimum observable range is about 300 m and maximum observable range is between 4-6 km (limited by signal to noise ratios for the DIAL measurement). For pulses near 650 ns, minimum and maximum range are closer to 200 m and 3-4 km, respectively. Pulse lengths below 650 ns have not been attempted because of the severe reduction in range observed. However, extending the definitions of the output pulse train to include pulses of 2 different lengths provides more flexibility to design a system to simultaneously observe near and far ranges.

An example of a more complex pulse train is given in Figure 1 (not drawn to scale) for the MPD instruments. For reference, these lidar systems use a single detector and single amplifier where pulses from online and offline wavelengths are interleaved in time. The example timing shown in Figure 1 alternates between online and offline lasers every 5 laser shots with 80% of the shots being longer and 20% being shorter. Two flags, with a combined 4 binary options, are used to direct any detected photons to a different channel of a multi-channel scaler.

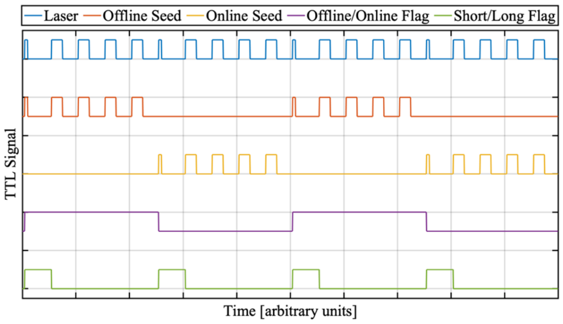

Figure 1: Example pulse train for simultaneous short and long pulses (not to scale for clarity)

This example pulse train would allow one to emit short pulses to see lower to the ground while maintaining longer, higher total energy, pulses. It would also reduce the number of short pulses compared to longer pulses because the signals required for observing closer to the ground need not be as strong. By altering the pulse length and the number of pulses, signal levels are more adaptable to scientific needs. Without changing any optical design or adding hardware complexity, this change provides what is in effect, a low-gain channel; typically, lidar systems providing the same capability require a separate set of receiver optics.

It is noteworthy that if the example pulse train described above was performed with a q-switched solid state laser, it would be challenging due to transient thermal conditions. Diode lasers have significantly higher wall-plug efficiency (in this case ~60%), meaning less input energy is lost as heat. The active lasing medium in a diode laser is significantly smaller (on the order of a few tens of microns thick), meaning waste heat can be more readily removed. Both significantly reduce thermal lensing effects. As a result, diode lasers significantly simplify the hardware design of a laser capable of performing such a complex pulse train.

4. Smart Switch for MPD

We have developed a timing control system that we call the "Smart Switch", which allows for up to 32 distinct pulse type definitions. For example, Figure 1 shows 2 definitions: a short pulse and a long pulse. The Smart Switch is an FPGA-based system capable of switching output pulse definitions from shot-to-shot, which allows for greater flexibility when designing an observational strategy. It incorporates the ability to subdivide pulses such that unique keys can be imparted to the outgoing laser pulse.

An example of the background subtracted signal counts that are observable with this Smart Switch is presented in Figure 2 from the MPD water vapor (WV) channel. In this case, long pulses of 1 µs and short pulses of 200 ns are interleaved at 50% duty cycle, i.e. every 4 shots of the laser cycle between WV online short, WV offline short, WV online long, and WV offline long. The laser is run at 8kHz (2 kHz for each pulse definition). Data shown is integrated for 1 minute and background subtracted. Note that there has been no optical change to the system to accommodate these measurements.

This example shows, what is in effect, a high and low gain channel. There are three noteworthy features of this design. First, the low gain channel allows for observations of clouds that are at higher resolution because the outgoing pulse is convolved with the scattering target in range. Second, the pulse lengths and duty cycle between short and long pulses are all completely adjustable so the effective gain of each channel is finely tunable. Third, as the laser amplifier and detector are shared among all 4 targets, forward modeling of the 4 channels could conceivably be used to blend the high- and low-gain channels effectively.

5. Conclusion

The present work focuses on a system that allows for the modification of laser pulse parameters for a semiconductor lidar system from shot-to-shot. This system takes its inspiration from pulse-compression waveforms that are created by some modern radar systems to preserve range resolution while emitting relatively long pulses. An FPGA-based system has been built that allows for the definition of up to 32 distinct pulse types and can interleave the different pulse definitions into a single output pulse train.

An example relevant to the MicroPulse DIAL (MPD) instrument was given where a high- and low-gain channel was created by varying the pulse length (and by extension total output laser power) between 2 pulse definitions without adding any additional optics or hardware.

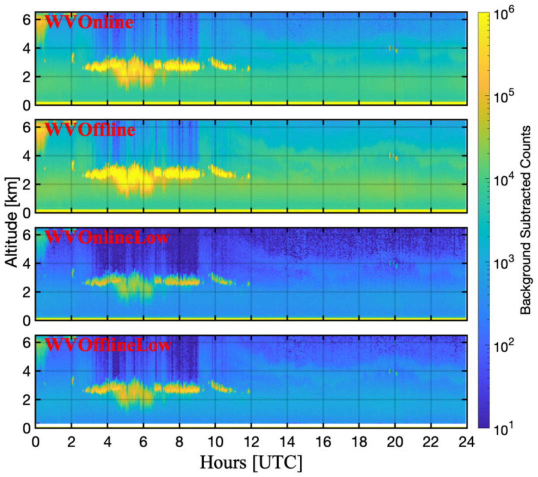

Figure 2: Photon counts from Long/Short pulse mode

6. References

[1] National Research Council, *Observing Weather From the Ground Up* (National Academies Press, 2009)

[2] National Research Council, *When Weather Matters* (National Academies Press, 2010)

[3] National Academies of Science Engineering and Medicine, *The Future of Atmospheric Boundary Layer Observation* (National Academies Press, 2018)

[4] M. A. Richards, J. A. Scheer, and W. A. Holm, *Principles of Modern Radar Vol. 1: Basic Principles* (SciTech Publishing, 2010)

[5] S. M. Spuler, K. S. Repasky, B. Morley, D. Moen, M. Hayman, and A. R. Nehrir, "Field-deployable diode-laser-based differential absorption lidar (dial) for profiling water vapor" Atmos. Meas. Tech., 8, 3, 1073–1087 (2015).

[6] R. A. Stillwell, S. M. Spuler, M. Hayman, K. S. Repasky, and C. E. Bunn, "Demonstration of a combined differential absorption and high spectral resolution lidar for profiling atmospheric temperature" Opt. Express, 28, 71–93 (2020).

[7] S. M. Spuler, M. Hayman, R. A. Stillwell, J. Carnes, T. Bernatsky, and K. S. Repasky, "MicroPulse DIAL (MPD) – a diode-laser-based lidar architecture for quantitative atmospheric profiling" Atmos. Meas. Tech., 14, 4593–4616 (2021).