Author's Response to Reviewers Comments (Review 1)
Title: Expanding Observational Capabilities of A Diode-Laser-Based Lidar Through Shot-To-Shot Modification of Laser Pulse Characteristics

The authors would like to first thank the reviewers for their time and for their thoughtful and constructive comments on our manuscript. The comments, taken from the provided reviews, have been copied in bullet format and addressed in the sub-bullets in blue. The line numbers for comments are referenced to the original draft and for responses to the revised draft. A pdf is included identifying the changes with blue text highlighting the additions and ~~red~~ text highlighting the removed elements.

<u>Reviewer #1:</u>

Major Comments:

- This problem of optimal combination of high res / high noise data and low res / low noise data seems rather current in imaging, especially in satellite imaging or astronomy. Principal component, wavelets and multiscale analyses are used in image fusion algorithms. Bayesian and hierarchical methods are very powerful but more complex. There is also regularized deconvolution with the Richardson-Lucy algorithm. May I suggest to append this section with a quick review and a first application of one of these algorithms on the available data from Figure 5, which is a great case? This would greatly strengthen the article in my opinion, and avoid this conclusion on a bit of a frustrating note.
    - We thank the reviewer for this comment and for highlighting a blind spot in our knowledge of the literature (searching "Image fusion" was immensely helpful). We have included the requested fused image based on a principal component analysis method and added some discussion and references to section 5.2 to introduce the topic. We have also included 5 new references: 3 summary articles and 2 more focused PCA articles. While the merge technique that we use has value, we do not believe that it is an adequate long term solution because it does not deconvolve the pulse width, leaving a bias mechanism uncontrolled. We have added text to indicate this to the manuscript. We are actively working to implement Poisson Total Variation (PTV), which is a regularized maximum likelihood estimator that is born from medical imaging, and is among the more complex image fusion methods. So we hope to have a more advanced method to fuse data in the future and will include those results in a future publication.

Minor Comments:

- Line 6: Be more precise (far range performance)
    - The authors agree with the reviewer that we have been a bit sloppy here insofar as the performance degrades by reducing the overall number of laser pulses emitted as Long pulses, which we note in Section 4. We intended to say that we have not completely sacrificed far range performance to gain short range performance. We have replaced "consistent" with "sufficient".
- Line 27: Replace "100s" with "hundreds"
    - Done. The changes are now on Lines 25 and 27.
- Line 37: Use a comma between "sensitivity" and "with"
    - Done
- Line 38: Complete the parenthetical. Comma between "ranges" and "and"

  - Done
- Line 38: “enable” should be “enabling”.
  - Done
- Line 50: Remove the 1.1. subsection
  - Done
- Line 91: Here and after, it is unclear what a block is. It is defined 2 paragraphs too late. Please move the definition.
  - Thank you for pointing out that this is unclear. We have introduced a definition of pulse blocks starting on Line 90.
- Figure 2: There seems to be a moist bias near 800 meters. Please comment.
  - There is a slight bias, quantifiable with the radiosonde data. We have included an average of all sonde comparisons to substantiate that in our new Figure 5. We have not identified the exact mechanism but speculate it occurs where signal-to-noise ratios are low due to telescope overlap considerations. What is not shown in Figure 2 is that when this happens, error bounds increase accordingly. We do believe that the accompanying increase in error encompasses this effect. We have added more discussion to section 5.1 to discuss this in greater detail.
- Line 165: A bit heavy. Consider reformulating.
  - We presume based on the location of the comment that you mean this to refer to “zenith opacity”. We have removed “zenith” as it is, in our understanding, not strictly needed but choose to leave “opacity” as it is the unit used to differentiate the emission lines in Figure 1 of Cadeddu et al. 2013.
- Line 170: Add “that is” after “one”.
  - Done
- Line 183: “corresponding” should be “correspond”.
  - Done
- Line 184: Why not use "Relative error", which seems more rigorous?
  - The change suggested by the reviewer has been made. Figure 4 now uses Relative error and the discussion in Section 5.1 has been updated accordingly.
- Figure 4: Consider using the terms "Absolute error" and "Relative error", labelling each panel, with a more detailed legend below.
  - Done
- Line 203: Replace “It is merely relevant that” with “What is more relevant is that”.
  - Done

<u>Reviewer #2:</u>

Major Comments:

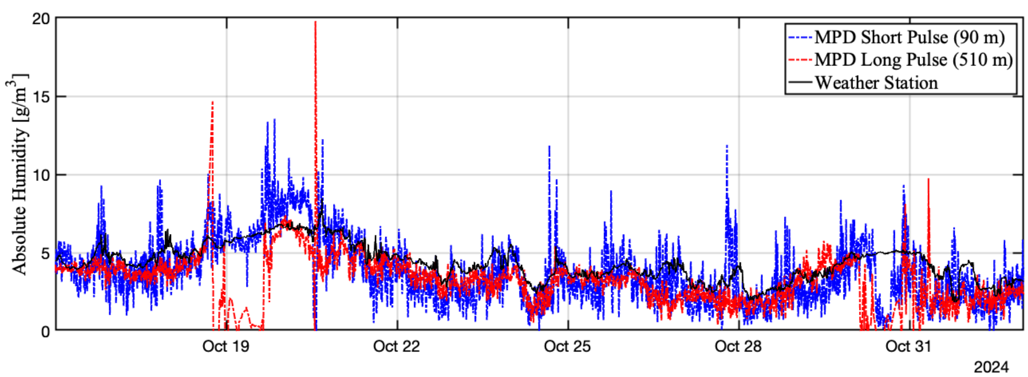
- The draft could benefit from a more quantitative discussion of the magnitude and relative weight of the different uncertainty sources associated with the short-range retrieval (e.g., signal strength changes due to incomplete overlap, background effects).
  - Thank you for pointing out that we have been a bit terse here. One of the most beautiful parts of altering laser pulse characteristics is that optics don’t change and no additional hardware is needed. This means that, by design, the optical alignment of the Long and Short pulses are identical. What this means practically is that everything is exactly the

same except the laser output average power. The MPD lasers output a pulse that is to first order a square pulse (there are rise times and fall times to consider still, but it is close) so the average power scales almost linearly with the pulse length. On short time scales, the SNR therefore is only affected by pulse length. On longer time scales, the background can change, but it changes the same for both pulse block types. Extending this all the way to error estimates: error bounds should always be higher for Short pulses than Long. We now discuss this in Section 5.1. Note, there are areas where we can squeeze in measurements with Short pulses that do not fit for long pulses (for example under low clouds). We discuss errors related to Figure 3 and have therefore also added more discussion to Section 4 highlighting this feature.

- Based on the plots in Figs. 2 and 3, there appears to be a slight low bias below 500 m, which reverses into a high bias between 500 m and 1 km.

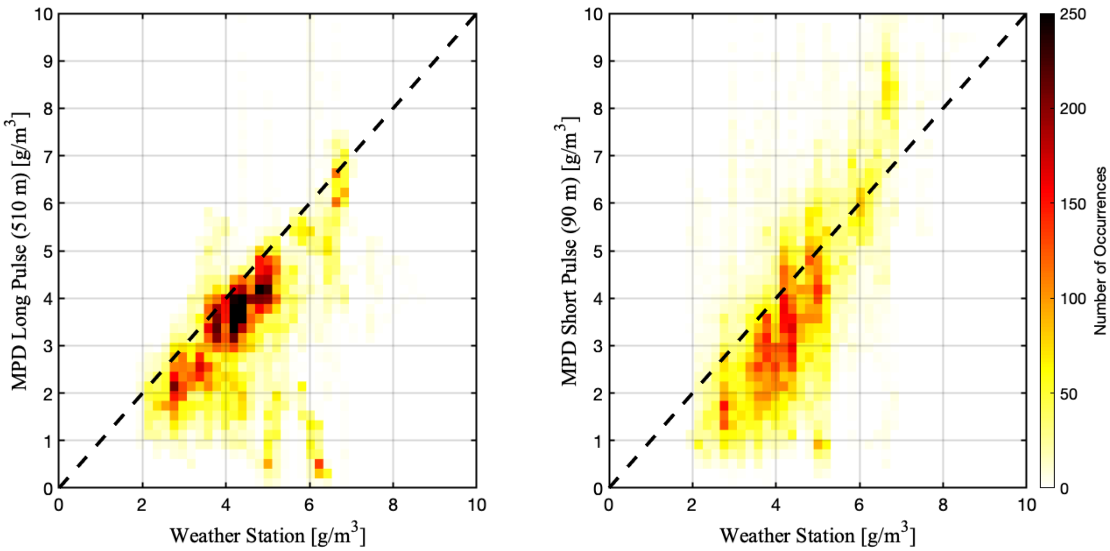
  There is a slight bias, quantifiable with the radiosonde data. We have included an average of all sonde comparisons to substantiate that in our new Figure 5. We have not identified the exact mechanism but speculate it occurs where signal-to-noise ratios are low due to telescope overlap considerations. What is not shown in Figure 2 is that when this happens, error bounds increase accordingly. We do believe that the accompanying increase in error encompasses this effect. We have added more discussion to section 5.1 to discuss this in greater detail.

- If available, a comparison with surface humidity measurements and the first 'valid' retrieval bin could clarify any potential low bias at the bottom of the short-pulse retrieval.
  - The requested analysis is below. Weather station data is available at a cadence of 5 seconds and the MPD data is processed at 4-minute resolution. We have smoothed the data to 20-minute resolution. In general, there is a higher measured absolute humidity for the weather station at the surface than for MPD at 90 m (short) and 510 m (long), which is expected given a canonical decreasing humidity with altitude. This is not necessarily true, for example the data we present in our Figure 4.



Response Figure 1: Time series of MPD and Weather Station data over the same time presented in Figure 2 of the manuscript. Note that MPD measurements and Weather Station measurements are independent estimates. In general, Short pulse mode is noisier as expected since it is outputting less laser power

Taking the time series from Response Figure 1 and converting it to 2-dimensional histograms is done in Response Figure 2. Weather station data is interpolated to the MPD data grid, allowing for a 1:1 comparison. The main excursions from the 1:1 line occur near October 19th and October 30th. From our Figure 2 from the manuscript, these times are affected by clouds and precipitation, respectively. For October 19th, the clouds are relatively low but high enough that the short pulses can see under them. On October 30th, it rained all day, meaning neither pulse length should be able to see below the clouds. As we note in the manuscript, within cloud and precipitation, MPD's measurements are biased very dry (and typically removed by data Quality Control).



Response Figure 2: 2-dimensional histograms of occurrence frequency of Weather Station and MPD absolute humidity pairs from Response Figure 1. The black dashed line is the 1:1 line.

We have elected not to include this analysis in the main manuscript because the range offset will necessarily produce a bias whereby the MPD should measure lower absolute humidity than the weather station assuming a canonical water vapor distribution that is decreasing with increasing altitude. It is not clear what the magnitude of this offset should be as it is weather system specific nor is it clear that this offset should be constant. This uncertainty makes it somewhat difficult to rigorously interpret the bias observed. As such, we prefer to lean on radiosonde observations to provide range information. We have included a summary of the radiosonde data in our new Figure 5.

Minor Comments:

- I agree with Julien Totems' comment regarding subsection 1.1; there is no need to separate it from the introduction.
    - The extra section header has been removed.