Laser Energy Monitor for Triple-Pulse 2-μm IPDA Lidar Application
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ABSTRACT
Integrated path differential absorption (IPDA) lidar is an active remote sensing technique for monitoring different atmospheric species. The technique relies on wavelength differentiation between strong and weak absorbing features normalized to the transmitted energy. An advanced 2-μm triple-pulse IPDA lidar was developed at NASA Langley Research Center for active sensing of carbon dioxide and water vapor simultaneously. The IPDA transmitter produces three successive laser pulses separated by a short interval (200 μs) with a repetition rate of 50Hz. Measurement of laser pulse energy accurately is a prerequisite for the retrieval of gas mixing ratios from IPDA. The design and calibration of a 2-μm triple-pulse laser energy monitor are presented. Due to the short interval between the three transmitted pulses, conventional thermal energy monitors underestimate the total transmitted energy. The design is based on a high speed, extended range InGaAs pin quantum detector suitable for separating the three pulse events. Pulse integration is applied for converting the detected pulse power into energy. The results obtained from the laser energy monitor were compared to an ultra-fast energy-meter reference for energy scaling and verification. High correlations between the pin energy monitor and the total transmitted energy were obtained. The objective of this development is to reduce measurement biases and errors using the triple-pulse IPDA technique.

Keywords: Laser energy monitor, triple-pulse laser, lidar, integrated path differential absorption lidar, carbon dioxide, water vapor, pulse detection

1. INTRODUCTION
Integrated path differential absorption (IPDA) lidar is suitable for remote sensing of different atmospheric trace gases [1-4]. Similar to differential absorption lidar (DIAL), IPDA relies on differentiation between strong and weak absorption features of the monitored gas with respect to wavelength. Unlike DIAL, IPDA depends on hard target return signals that are dependent on the gas content over the whole range of the measurement column. In order to retrieve the gas content, the target signals are normalized to the transmitted laser energy. IPDA hard target return and laser energy monitor provide strong signals that lead to high signal-to-noise ratio (SNR) IPDA measurement, as compared to DIAL, but with the loss of the range-resolved measurement capability. High SNR significantly enhances the measurement sensitivity and accuracy of the IPDA lidar technique used in several recent atmospheric remote sensing applications [1-5].

IPDA lidar operating at the 2-μm wavelength are suited for monitoring atmospheric carbon dioxide (CO2) [5-7]. This is due to the existence of several strong CO2 absorption features within this wavelength region. Nevertheless, other atmospheric spices exhibit some absorption, in the same wavelength region, which cause interference with CO2 measurement. Among these spices, water vapor (H2O) is the dominant molecule interfering CO2 measurement in the 2-μm. In addition, converting CO2 measurement into dry-air mixing ratio require knowledge of H2O beside atmospheric temperature and pressure. To address this issue, an airborne triple-pulse 2-μm IPDA lidar has been integrated and evaluated at NASA Langley Research Center (LaRC) for active sensing of CO2 and H2O simultaneously [7-9]. The triple-pulse IPDA development is based on the successful demonstration of the airborne double-pulse IPDA for CO2 measurements [5-6, 10]. In this triple-pulse IPDA, the 2-μm laser transmitter produces three successive laser pulses separated by 200 μs interval, with 50 Hz repetition rate. The wavelengths of the transmitted pulses are tuned and locked with respect to CO2 R30 absorption line center. Each pulse is tuned and locked to different wavelength, which is switched dynamically during the separation time. The IPDA tuning allows H2O measurements using the first and second pulses, and CO2 measurements using the second and third pulses [7-8].

Differential optical depth of the measured gas is the main IPDA lidar product. The measured differential optical depth, Δτ, is defined by
\[
\Delta \tau(\lambda_{\text{on}}, \lambda_{\text{off}}) = \log_e \left( \frac{P_{\text{off}} \cdot t_{\text{off}} / E_{\text{off}}}{P_{\text{on}} \cdot t_{\text{on}} / E_{\text{on}}} \right)
\]

where \( P \) (in W) is the return power, \( t \) (in s) is the return pulse width, \( E \) (in J) is the transmitted energy, and \( \lambda_{\text{on}} \) and \( \lambda_{\text{off}} \) are the on-line and off-line wavelengths, corresponding to high and low absorptions, respectively. Measurement of \( \Delta \tau \) is the initial critical step in the retrieval of gas column mixing ratio. As shown in Equation 1, \( \Delta \tau \) measurement is directly related to measurement of the integrated pulse energy over the pulse interval. IPDA measurements are challenging due the large dynamic range of the transmitted energy and the return signal over the pulse interval. In addition high accuracies of these measurements are required. Table 1 presents examples of these signals, obtained from the double-pulse IPDA lidar [5]. These results indicate at least 12 orders of magnitude between the transmitted and return radiation energies. Although these results are exaggerated, since only a sample of the transmitted energy has to be measured, other practical consideration includes optical and electronic requirements for the energy monitor and the target return detection systems. For example, detection systems used for measuring hard target returns require high-gain and low-noise to enhance sensitivity. Detection systems used for energy monitors require low-gain to avoid saturation, while shot-noise typically dominates the sensitivity. Therefore, it is difficult to measure both signals using a single detection system.

This paper presents the design and calibration of a 2-\( \mu \)m triple-pulse laser energy monitor. Similar to the double-pulse IPDA, the design is based on a high-speed, extended range InGaAs pin quantum detector suitable for separating the pulse events for each laser shot. Energy monitor calibration is based on correlating the pin detector measurement, of a sample of the transmitted beam, to the total transmitted energy measured using a commercial high-speed energy-meter. Section 2 describes the laser energy monitor setup within the IPDA instrument. Section 3 details the calibration transfer between the energy-meter reading and its analog output for synchronization with the laser pulses. Section 4 details the calibration transfer from the energy-meter analog output to the integrated energy monitor detector. Section 5 discuss the significance of the linearity of the energy monitor, with concluding discussion in section 6.

## 2. LASER ENERGY MONITOR SETUP

Figure 1 shows a schematic of the 2-\( \mu \)m triple-pulse IPDA lidar transmitter setup. The laser enclosure contains the lidar transmitter, which includes a 2-\( \mu \)m triple-pulse laser, steering optics and energy monitors. Two steering mirrors, M1 and M2, direct the laser output to a 6\( \times \) beam expander formed by X1 and X2 mirrors. Both M1 and M2 exhibit 99% 2-\( \mu \)m reflectivity. Therefore, 1% radiation leak from M1 is directed to an integrating sphere through a neutral density filter, NDF. A 300-\( \mu \)m diameter InGaAs photodiode (Hamamatsu; G8423-03) is mounted on the integrated sphere and used as energy monitor detector (EMD) to observe the transmitted laser pulse energy. NDF and the sphere were set to insure beam uniformity and avoid saturation for EMD. Similarly, part of the 1% scattered radiation, out of M2, is detected by a 75-\( \mu \)m diameter, high-speed InGaAsSb photodiode (IBSG; PD24-005-HS) and is used as pulse monitor detector (PMD) to confirm the seeding of the transmitted laser pulses. PMD position was set to insure maximum unsaturated detected signals. Figure 2 shows the spectral response and quantum efficiency calibration of both detectors. Simultaneously, EMD and PMD signals are digitized and recorded using two-channel, 12-bit analog-to-digital converter card (Agilent; U5303A) at 1 GS/s rate (1 ns sampling time). The digitizer card is mounted inside the data acquisition computer. DC coupling of EMD to the digitizer was conducted through a trans-impedance amplifier (FEMTO; DHPCA-100), set to a gain of \( 10^3 \) V/A with 80 MHz bandwidth. PMD was connected directly to the digitizer 50 \( \Omega \) input. Detectors record synchronizations are achieved using the laser Q-switch trigger signal. The 21.4 mm expanded beam, out from X2, is then steered toward the receiver telescope, using S1 and S2 mirrors, to be transmitted coaxially through the lower surface of the telescope secondary, T2.

For EMD calibration purpose, the expanded beam is focused using a lens, L, onto the detection head of a commercial calibrated high-speed energy-meter (Gentec-eo; MACH 6). This energy-meter is capable of measuring up to 200 mJ

<table>
<thead>
<tr>
<th>Line, 1.5 km</th>
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</thead>
<tbody>
<tr>
<td>E (mJ)</td>
<td>P (( \mu )W)</td>
<td>t (ns)</td>
<td>( E / E_{\text{R}} )</td>
<td></td>
</tr>
<tr>
<td>4 GHz On-Line</td>
<td>90.2</td>
<td>2.7</td>
<td>214.1</td>
<td>5.78\times10^{-13}</td>
</tr>
<tr>
<td>Off-Line</td>
<td>50.9</td>
<td>2.9</td>
<td>333.6</td>
<td>9.67\times10^{-13}</td>
</tr>
<tr>
<td>3 GHz On-Line</td>
<td>87.7</td>
<td>67.0</td>
<td>205.5</td>
<td>1.38\times10^{11}</td>
</tr>
<tr>
<td>Off-Line</td>
<td>48.7</td>
<td>43.2</td>
<td>352.2</td>
<td>1.52\times10^{11}</td>
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</table>
Figure 1. A schematic for the 2-µm triple-pulse IPDA lidar transmitter setup. Energy monitor detector (EMD) and pulse monitor detector (PMD) are integrated within the laser enclosure. Lens L and pyroelectric thermal detector RD are installed to collect the IPDA transmitted output during EMD calibration. L and RD are removed during normal instrument operation.

Figure 2. Spectral response (left) and quantum efficiency (right) calibration of the InGaAs pin and InGaAsSb pn photodiodes used for energy monitor detector (EMD) and pulse monitor detector (PMD), respectively. Calibration was conducted at 20°C and zero bias voltage with respect to a calibrated PbS reference detector. Red circles mark the results obtained at 2.050 µm, the IPDA lidar operating wavelength.

Pulses at 200 kHz repetition rate. The detection head of the energy-meter consists of a pyroelectric thermal reference detector, RD (Gentec-eo; M6-12.5-PY). The thermal detector is coupled to the measured radiation beam through an integrating sphere, with an effective aperture of 12.5 mm. This allows RD to measure the whole transmitted energy during the energy monitor calibration and to correlate these measurements to EMD records. RD have the sensitivity and dynamic range suitable for directly measuring pulsed laser energy. RD inherently integrates the input radiation power to produce an output signal with a peak-to-peak value proportional to the pulse energy. EMD uses a quantum detector, which provides an electrical signal proportional to the radiation power. Therefore, to monitor laser pulse energy, the detector output has to be integrated with respect to time during data processing. The energy-meter instrument provides a USB connection to the computer for instrument control and data display and record. Once initiated, the energy-meter records the energy of a sequence of pre-selected number of pulses. No synchronization between the laser pulses and the energy-meter could be achieved. In addition, the instrument provides an analog output to monitor RD voltage profile record per shot. Therefore, EMD calibration was conducted in two steps. The first step transfers the energy-meter calibration to RD, and the second step transfers the calibration from RD to EMD.
3. ENERGY-METER CALIBRATION TRANSFER

The 2-µm triple-pulse laser produces three pulses using a single pump pulse. The energies of the individual output pulses are proportional to the pump pulse energy. The energy-meter is capable of resolving 5-µs pulse separation, which is suitable for the 200-µs 2-µm pulse separation. Nevertheless, the energy-meter cannot distinguish the pulse sequence event to separate the individual pulse energy of the first, second and third pulses. Figure 3 shows the energy-meter measurements for 500 shots of the 2-µm triple pulse laser, which consists of 1500 pulses. Discrete levels distinguish the energy of pulses 1, 2 and 3, which are separated during data processing. Energy records observed close to zero indicates unregistered pulses, although these pulses appear at the analog output. Figure 4 shows the analog output records for the same pump energy levels.

For calibration transfer between the energy-meter and the analog output (RD profile), the 2-µm pump energy was set to a fixed value. Then, the triple-pulse energies were recorded using the energy-meter, while recording the analog output profiles using the digitizer. The records were obtained for 500 shots, after which the pump laser energy was changed for the next record. For each record, the energy-meter unregistered data were rejected and the mean energy for each pulse was calculated from the discrete levels. RD analog output was processed by subtracting the background, using pre-trigger samples, and observing the maximum value for each pulse, which corresponds to the peak-to-peak voltage. Figure 5 shows the variation of the 2-µm output pulse energy with respect to the pump laser energy. Pulse energy is obtained as the mean value of the energy-meter records. The total energy is the sum of the three pulse energies at the same pump level. The figure also shows the correlation between the analog output pulse peak and the measured energy confirming linear relation. This calibration transfer between the energy-meter energy record and RD pulse profile, at the analog output, allows synchronizing the instrument to EMD.

![Figure 3. Energy-meter records for 500 shots from the 2-µm triple-pulse laser using 703.202 mJ (left) and 946.466 mJ (right) pump energy. The 500 shots consists of 1500 laser pulses with pulse 1, pulse 2 and pulse 3 for each shot.](image)

![Figure 4. Energy-meter analog output, corresponding to RD measured profile, for a single shot 2-µm triple-pulse laser using 703.202 mJ (left) and 946.466 mJ (right) pump energy. Pulse energy is proportional to the peak value of the analog output signal profile after background subtraction.](image)
4. LASER ENERGY MONITOR CALIBRATION

Synchronization between RD and EMD was achieved by triggering two digitizers with the same laser Q-switch signal. The record length of the RD digitizer was set to 10k samples to accommodate the long thermal detector pulse, as indicated in figure 4. Figure 6 shows samples of the triple-pulse EMD output, at two different energy levels, and the variation of the first pulse with the pump energy. Due to the fast response of the pin detector, the record length of the EMD digitizer was set only to 3k samples. RD and the corresponding EMD data were recorded for 500 successive laser shots for each pump energy level. Analysis for EMD records includes background subtraction and pulse integration. The background was defined as the mean value for the pre-triggers samples from 0 to 1 µs. Then, pulse integration was performed from 1.2 to 2.5 µs using the trapezoidal rule. Longer integration period was used to accommodate jitters between successive pulses or drifts due to increasing pump energy, as indicated in figure 6. RD data were analyzed using the same procedure described in the previous section. Figure 7 shows the variations of the normalized RD peak and EMD pulse integration with the shot number. A high correlation coefficient, of 0.9885, was observed between the two records. Converting RD peak value into energy, using the calibration presented in figure 5, relates the EMD pulse integration to the energy. These procedures were repeated for the three pulses at different pump energy levels for each shot. Figure 7 shows the accumulated single-shot data for these records. The single-shot data were averaged using a fixed energy bin of 0.25 mJ. The integration mean was calculated for each bin as shown in the same figure. Curve fitting was applied to the averaged data after eliminating the five end-points from the lowest and highest energy. Linear curve fitting, given in equation 2, was applied to the data up to 17.5 mJ. Higher energies indicated nonlinear response that was fitted using third order polynomial, given in equation 3.

\[
E = 0.306 \cdot I - 0.816; \quad 6 < E < 17.5 \text{ [mJ]; } 17 < I < 54.5 \text{ [V} \cdot \text{ns]} \tag{2}
\]

\[
E = 7.567 \times 10^{-5} \cdot I^3 - 7.775 \times 10^{-3} \cdot I^2 + 0.557 \cdot I - 1.692; \quad 6 < E < 20.7 \text{ [mJ]; } 17 < I < 60.8 \text{ [V} \cdot \text{ns]} \tag{3}
\]

where \( E \) is the pulse energy in mJ and \( I \) is the EMD pulse integration in V-ns.

During EMD setup integration, the peak signal, at maximum energy, was set to less than 1V to avoid TIA saturation, as indicated in figure 6. Thus, EMD nonlinearity at higher energies are probably due to pin detector approaching saturation. Figure 8 shows the implementation of EMD calibration for monitoring the transmitted energy per shot for the three laser pulses. This was done by repeating the experiment while applying equation 3 to directly convert the pulse integration into energy. Results indicated high correction between EMD and actual transmitted energy for pulses 2 and 3, where the energies lies within the linear region of the calibration. Fluctuations mis-match is expected, resulting in less than perfect 1.0 correlation coefficient, due to the different setups. Lower correlation for pulse 1 is due to saturation. Although saturation does not change the mean energy, it results in suppressing EMD fluctuations. According to equation 1, this may lead to significant bias in the normalization process for the differential optical depth calculations. On the other hand, suppressing the fluctuation results in inaccurate estimates of random errors, since the uncorrelated measurements adds to system noise. An option to reduce such biases is to avoid IPDA operation for high pulse energies.
Signal-to-noise ratio (SNR) affects the random error, or sensitivity, of the IPDA lidar. The differential optical depth random error $\delta(\Delta \tau)$ is defined by [2]

$$\delta(\Delta \tau) = \frac{1}{2} \sqrt{\frac{1}{\text{SNR}_{P,\text{on}}^2} + \frac{1}{\text{SNR}_{P,\text{off}}^2} + \frac{1}{\text{SNR}_{E,\text{on}}^2} + \frac{1}{\text{SNR}_{E,\text{off}}^2}}$$

where SNR$_{P,\text{on}}$ and SNR$_{P,\text{off}}$ are the on and off-line return power SNR, respectively and SNR$_{E,\text{on}}$ and SNR$_{E,\text{off}}$ are the on and off-line transmitted energy SNR, respectively. Equation 4 indicates that $\delta(\Delta \tau)$ is limited by the lowest SNR among the four terms. Therefore, maximizing the transmitted energy SNR is required to allow $\delta(\Delta \tau)$ to be dominated by the on-line return signal, which is typically the lowest signal due to strong absorption (for example, see Table 1 at 6.1 km).

Table 2 presents the results of the statistical analysis of the data presented in figure 8 for EMD. The table also compares the SNR obtained from the measured energy standard deviation, SNR$_E$, and the SNR obtained from the standard deviation of the difference between the measured and transmitted energies, SNR$_{E,PD}$. SNR$_E$ includes both laser energy fluctuations and detection noise, whereas SNR$_{E,PD}$ only focuses on detection noise, since the laser fluctuations were eliminated by subtraction. SNR$_{E,PD}$ is the true SNR that is applied in equation 4. Results indicate the significance of the per-shot analysis, where the laser fluctuations can be eliminated. EMD cannot distinguish the fluctuation form noise. But
Figure 8. Correlation between triple-pulse 2-μm IPDA transmitted laser energy and energy monitor, EMD, results per laser shot for pulse 1 (top), pulse 2 (middle) and pulse 3 (bottom). Transmitted laser energy, per-shot, was measured using RD. High correction between EMD and actual transmitted energy is observed for pulses 2 and 3, while lower correlation result for pulse 1 due to saturation.

Table 2. Sample results of the transmitted energies and the return signals obtained from the 2-μm double-pulse IPDA lidar at two different altitudes and different operating wavelengths [4].

<table>
<thead>
<tr>
<th></th>
<th>Mean(E)</th>
<th>Std(E)</th>
<th>SNR_E</th>
<th>Std(E-PD)</th>
<th>SNR_E-PD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mJ)</td>
<td>(mJ)</td>
<td>Mean(E)/Std(E)</td>
<td>Mean(E)/Std(E-PD)</td>
<td></td>
</tr>
<tr>
<td>Pulse 1</td>
<td>19.44</td>
<td>0.21</td>
<td>94.5</td>
<td>0.24</td>
<td>82.2</td>
</tr>
<tr>
<td>Pulse 2</td>
<td>13.64</td>
<td>0.27</td>
<td>49.9</td>
<td>0.12</td>
<td>116.4</td>
</tr>
<tr>
<td>Pulse 3</td>
<td>8.44</td>
<td>0.29</td>
<td>29.6</td>
<td>0.12</td>
<td>69.1</td>
</tr>
</tbody>
</table>

if the fluctuations were treated correctly they should cancel out through energy normalization of equation 1. This is indicated in the results of pulses 2 and 3, where SNR almost doubles after eliminating the fluctuations. On the other hand, results of pulse 1 indicate the influence of the energy monitor non-linearity. Due to saturation, both laser energy fluctuations and noise were underestimated. Therefore, eliminating the laser fluctuation from pulse 1 tends to add more fluctuations leading to increase the standard deviation and reduce SNR.

6. CONCLUSION

IPDA lidar is a promising remote sensing technique for measuring atmospheric trace gases. Triple-pulse IPDA lidar operating at the 2-μm wavelength has demonstrated suitability for simultaneous measurement of atmospheric CO₂ and H₂O. Optical depth is the main IPDA product, which is obtained through normalizing the hard target return signals to the laser transmitted energies. This requires accurate measurement of the transmitted laser pulses energies, simultaneously while operating the instrument. Energy monitor detector, based on extended range InGaAs pin photodiode, was integrated inside the triple-pulse laser to monitor the transmitted energy per shot. EMD was calibrated with respect to the laser transmitted energy using a high-speed energy-meter. The energy-meter is based on small-area pyroelectric detector. Calibration transfer was conducted in two steps. The first step transfers the energy-meter calibration to RD, and the second step transfers the calibration from RD to EMD. Energy measurement and monitoring results, per-pulse, are well correlated at lower energy levels (less than 17.5 mJ). The decrease of the correlation at higher energy levels suggests some saturation effects. Saturation does not change the mean energy measurements, since it's accounted for during calibration. Saturation results in suppressing per-pulse energy fluctuations, which leads to bias and increased random...
error in the differential optical depth calculations. These results address the significance of the linearity of the laser energy monitor for IPDA lidar applications.

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