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Characterization of a 16-Bit Digitizer for Lidar Data Acquisition

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Acronyms

ADC	analog-to-digital conversion
CAMAC	computer-automated measurement and control
D/A	digital-to-analog converter
DIAL	differential absorption lidar
lidar	light detection and ranging
PCI	personal computer interface
PMT	photomultiplier tube
S/H	sample and hold
UAV	unpiloted atmospheric vehicle

Abstract

A 6-MHz 16-bit waveform digitizer was evaluated for use in atmospheric differential absorption lidar (DIAL) measurements of ozone. The digitizer noise characteristics were evaluated, and actual ozone DIAL atmospheric returns were digitized. This digitizer could replace computer-automated measurement and control (CAMAC)-based commercial digitizers and improve voltage accuracy.

Introduction

The waveform digitizer is a critical component of lidar detection systems; it transforms the analog detector output into a digital signal by measuring the signal voltage in a discrete time interval determined by an external clock. The accuracy of the digital voltage level increases with the digitizer bit level. Technology has advanced to the point where 8- and 12-bit waveform digitizers are commercially available and commonly used in computer-automated measurement and control (CAMAC) crates, which are readily interfaced to computer systems. These systems have worked well for ground and aircraft-borne lidar systems, but future lidar systems will require higher voltage accuracy and eventual deployment on unpiloted atmospheric vehicles (UAV) and orbiting spacecraft. In these situations, payload weight, volume, and available power are severely restricted. Langley Research Center is actively pursuing the development of small, lightweight differential absorption lidar (DIAL) receiver systems for deployment on UAV aircraft and eventually on spacecraft. In this situation, CAMAC crates cannot be used, and the need for higher accuracy has led to the investigation of advanced digitizer technologies.

Waveform digitizers have rapidly advanced to the point where small, 16-bit lightweight, low-power consumption digitizer modules are available. The advantage of 16-bit digitizers is shown in figure 1, in which the performance of 8-, 12-, and 16-bit digitizers is compared. The 16-bit resolution of 0.046 mV/step (assuming a V_{max} of 3.0 V) is important, especially for space deployment, where lidar returns will

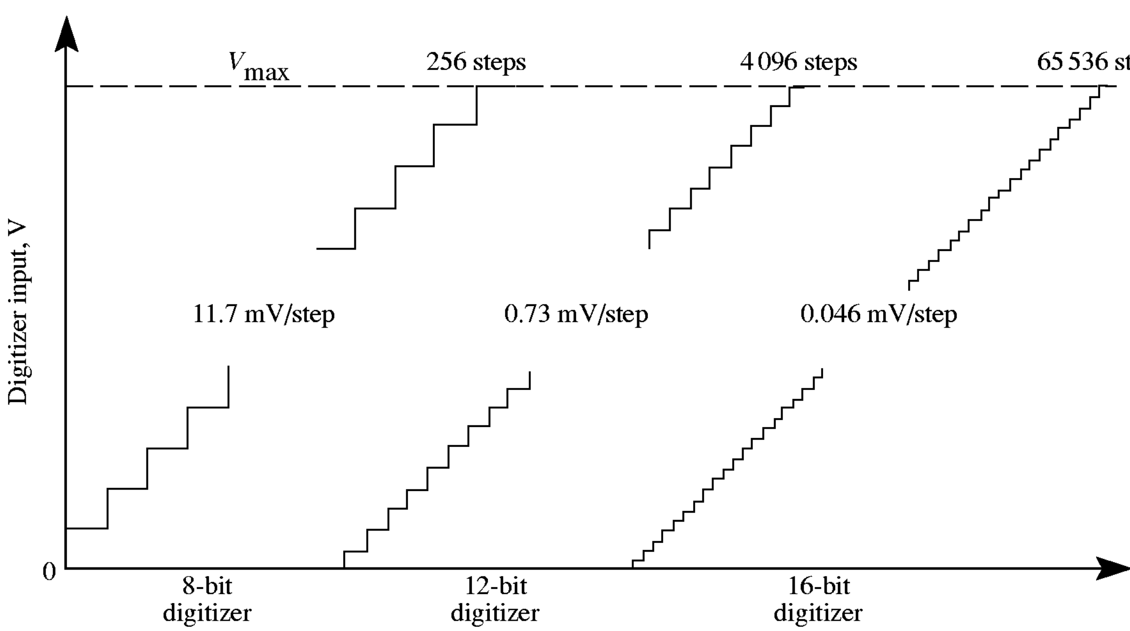


Figure 1. Resolution for 8-, 12-, and 16-bit digitizers, assuming a maximum of 3 V.

cover very long distances, requiring improved resolution or sensitivity. While voltage resolution depends on the digitizer bit number, the time or range cell depends on the clock frequency. For example, a clock frequency of 1 MHz corresponds to a 300-m range cell, whereas a clock frequency of 6 MHz results in an altitude range cell resolution of 48 m.

This study will report preliminary results on the performance of a small 16-bit waveform digitizer that can be interfaced easily to a computer, allowing substantial reduction in weight and volume over CAMAC-based digitizer systems. Also, these new digitizers are relatively inexpensive and may soon see widespread use in DIAL receiver systems.

Experimental Setup

A schematic of the 16-bit waveform digitizer (Edge Technology, ET 2668) receiver system investigated in this study is shown in figure 2 and was used to digitize actual lidar atmospheric returns. The maximum data acquisition rate of this 16-bit digitizer is 6 MHz. The digitizer system was typically operated at a clock frequency of 5 MHz and a laser trigger rate of 30 Hz for testing with a DIAL lidar system. A digital input-output board (PCI-32HS, National Instruments) was used to read the digitizer output into the computer. The power supply for the digitizer consisted of a 6-V battery to minimize noise input. The typical power requirement for the digitizer system was 2.8 W and weighed approximately 2.3 kg. The manufacturer of the 16-bit digitizer guarantees no missing codes over the operating temperature range (0° to 70°C). The receiver system used a photomultiplier as the lidar detector (Electron Tubes, 9214Q). The amplifier used on the photomultiplier tube (PMT) output was an inverting amplifier with the gain adjusted such that the maximum voltage output was 1.5 V for the actual lidar returns processed. The arbitrary waveform generator was used to test the linearity of the 16-bit analog-to-digital conversion (ADC) and will be described in more detail later.

A schematic of the 16-bit, 6-MHz tracking digitizer is outlined in figure 3. For operation, the system requires only a clock, trigger, analog input, and power supply; it is a two-stage subranging analog-to-digital converter or digitizer. Subranging digitizers offer superior speed and resolution compared to

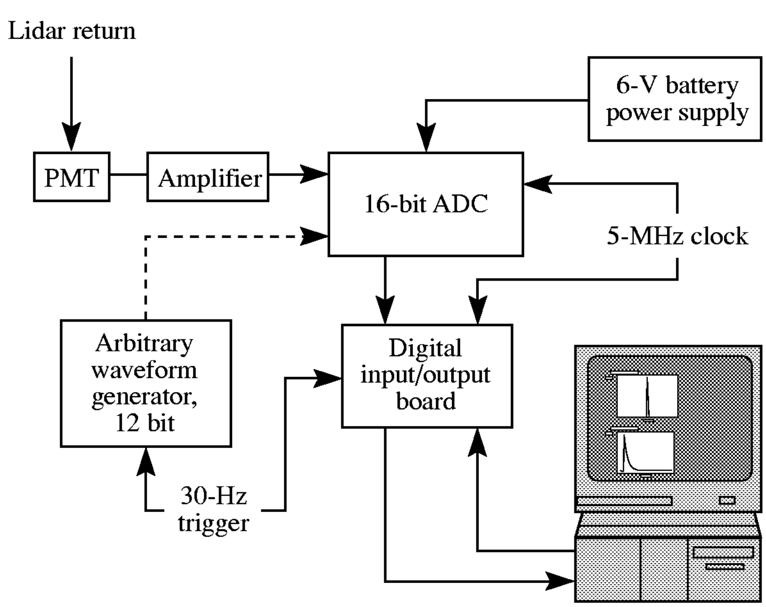


Figure 2. Block diagram for lidar receiver system.

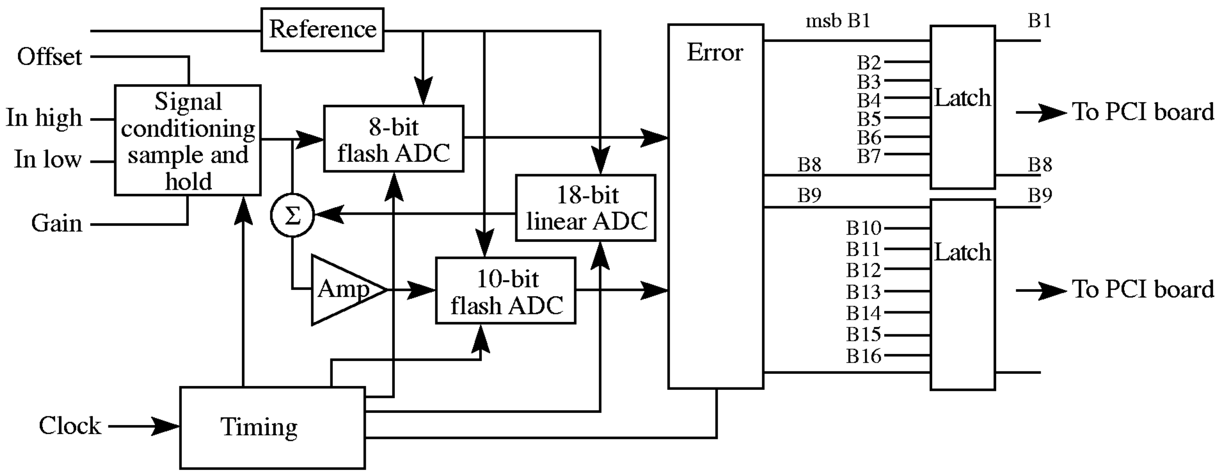


Figure 3. Block diagram of 16-bit digitizer architecture; Σ refers to sum operation.

successive-approximation converters, which have an upper limit conversion speed of approximately 1 µs for 12 bits (ref. 1). The 16-bit subranging digitizer system used in this study works by switching the sample and hold (S/H) circuit into a hold mode and quantizing the input signal with a flash converter. Flash converters consist of comparators and logic gates, which quantize the input signal; they are limited in the number of bits because the number of comparators required increases exponentially with the bit resolution (refs. 2 and 3). In this system, the use of two flash converters (10 bit and 8 bit), rather than one, enhances the speed of the digitizer because fewer switching mechanisms are required. The second flash converter, which receives input from the digital-to-analog converter (D/A), quantizes a difference signal that is sent to the digital correction logic to generate the final output. The difference signal is produced by subtracting the output of the D/A from the signal initially sampled by the S/H circuit. The D/A converts the digital approximation of the analog signal generated by the first flash converter back into an analog signal that is compared with the analog signal in the S/H circuit. Thus, the output of the first flash converter is corrected by a feedback into the D/A and a comparison is made with the initial input signal in the S/H circuit. Note that the second flash converter has some overlapping bits with the first flash converter, which functions as the error check. Also, the 8-bit flash converter completes the 16-bit conversion because the first flash converter is only 10 bits.

The flow of data from the 16-bit digitizer is regulated by data latches that capture the data (i.e., the data are valid) at specific time intervals relative to the timing of the digitizer. A schematic of the digitizer timing is shown in figure 4. The clock line initiates the conversion process, and its input pulse must remain high for a minimum of 10 ns. The clock sets the sample and hold amplifier in the hold mode and the sample line low for 7 ns. After a delay of 60 ns, the sample line triggers the transfer line into a high state. Data $N - 1$ is valid 30 ns after the start pulse and while the transfer line is high. The transfer line is not used in the setup of the 16-bit digitizer; instead, the clock trigger sets the data latches and starts the read function on the personal computer interface (PCI) board. Thus, the data read is one cycle behind the conversion process. This clock was 5 MHz, which typically is used for ozone lidar measurements. The PCI board receives a 30-Hz laser trigger pulse, which is synchronized with the 5-MHz clock. The 30-Hz trigger (50 Hz was also successfully implemented), in effect, activates the PCI board, which then reads data at the rate of the external clock (5 MHz). The 30-Hz input is the trigger used to fire the laser for ozone lidar measurements. The software that controls the PCI board is written in National Instruments LabVIEW. Data are plotted on the display in real time, relative to the 30-Hz trigger. The operator inputs the number of laser returns to store and average. The analog digitizer input can range from +1.5 V to –1.5 V, but the software is written to use only positive voltages.

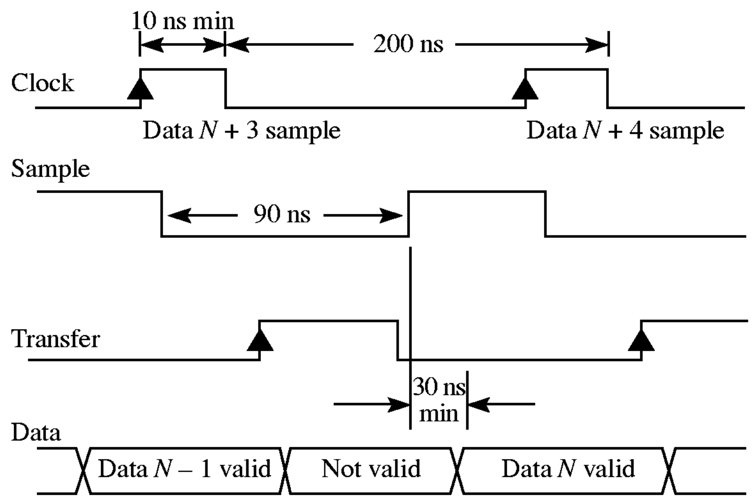


Figure 4. Timing diagram for 16-bit digitizer.

Ground-based ozone DIAL measurements were made by using the existing Nd-YAG pumped dye laser system (ref. 2). Briefly, this system consists of two Nd-YAG lasers, one for the DIAL "on-line" and one for the "off-line" wavelengths. Each Nd-YAG is doubled and then pumps a dye laser, which in turn is doubled into the ultraviolet. These pulses are then transmitted into the atmosphere.

The atmospheric scattered laser light is collected by a 30-cm diameter telescope. Light from this telescope is passed through a 300-nm narrowband filter and then focused onto a PMT optical detector. The PMT was usually gated on after the laser fired, and the gate "on" time was 300 μs for the on-line return, followed by 300 μs for the off-line return.

Results and Discussion

The 16-bit digitizer will be characterized based on its noise output and then compared to the noise level of the current CAMAC 12-bit digitizer. The digitizer will also be characterized for linearity by using an arbitrary waveform generator, as shown in figure 2. Finally, the results of actual ozone DIAL atmosphere returns with the "on" and "off" wavelengths (set to the same wavelength) will be presented. The results of actual ozone DIAL atmosphere returns with the on and off wavelengths (set to different wavelengths) will also be presented to produce an actual ozone profile.

The baseline noise levels during the 300-μs PMT gate-open time for the 16-bit digitizer are shown in figure 5. Trace A is the noise level for the digitizer in the open air unshielded, whereas for trace B, the digitizer was shielded in a grounded metal box to decrease the noise. When the digitizer was disconnected from the lidar system amplifier, the noise level decreased, as shown in trace C. The noise level (peak-peak) for the shielded system is 20-bit step numbers (0.915 mV). This level would be approximately 1 step on a 12-bit digitizer. Thus, the 16-bit digitizer can detect signal levels of 46 μV above the baseline noise of 0.915 mV, while a 12-bit digitizer is limited to signal levels of 732 μV above the baseline noise. This higher resolution is particularly useful in stratosphere measurements where water vapor densities are low and also in regions of low ozone density.

A comparison of noise levels for actual lidar returns for a CAMAC 12-bit ADC (currently used in the DIAL system) and the Edge Technology 16-bit ADC is shown in table 1. The signal-to-noise ratio is similar for the two digitizers. Noise levels for both digitizers are less than the 12-bit ADC resolution of

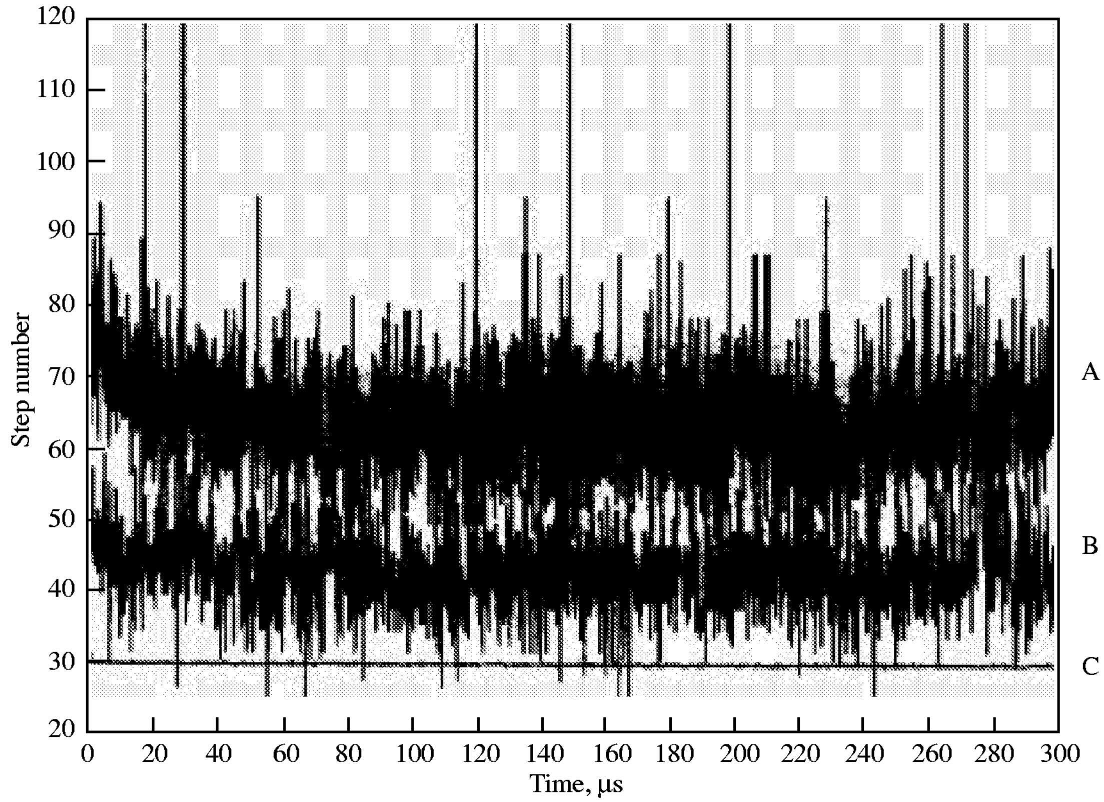


Figure 5. Lidar system noise tracers: A, total noise with open, unshielded digitizer; B, total noise with digitizers shielded in metal box; and C, digitizer disconnected from lidar system input.

0.73 mV/step. The noise level was the standard deviation of the baseline for five measurements obtained from an actual lidar system. The signal-to-noise ratio was calculated by averaging five actual lidar returns and dividing by the standard deviation.

Table 1. Comparison of Noise Levels for Actual Lidar Returns for 12-Bit and 16-Bit ADC

Lidar returns	Signal-to-noise ratio	Noise level
Current 12-bit ADC	95 (off-line) 230 (on-line)	0.244 mV (off-line) 0.244 mV (on-line)
New 16-bit ADC	125 (off-line) 360 (on-line)	0.146 mV (off-line) 0.146 mV (on-line)

An exponential output from an arbitrary function generator was input to the 16-bit digitizer and used to test the linearity of the 16-bit digitizer. Plots of 16-bit digitizer output (mV) versus time (figs. 6 and 7) are linear for exponential functions with generator time constants of 25, 28, 42, 60, and 82 µs. Specifically, figure 6 displays the linearity of the first 11 bits or 46 mV of the 16-bit digitizer. Figure 7 tests the linearity of the 16-bit digitizer up to 15 bits or 685 mV. It is apparent that the 16-bit digitizer offers sufficient linearity for the full range of bits for the input voltages between 0 and +1.5 V. Digitizer nonlinearity is considered the primary source of error in DIAL measurements (ref. 3).

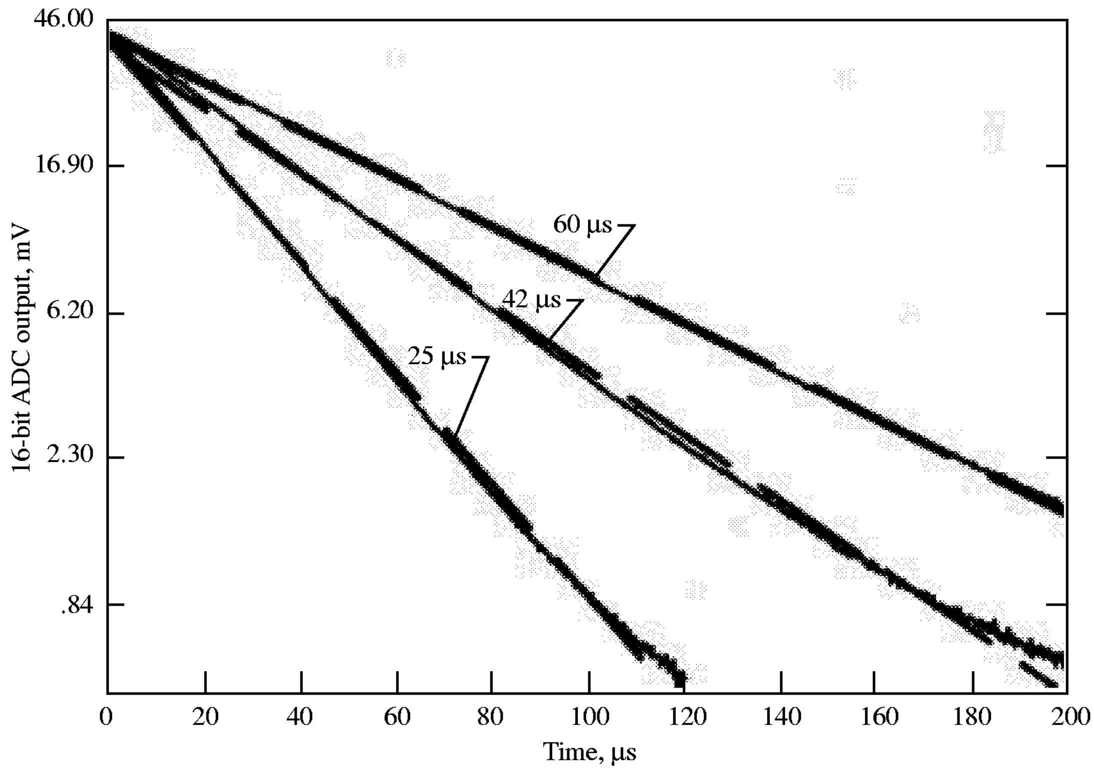


Figure 6. Digitizer linearity plots (natural log scale) using an arbitrary function generator with exponential time constraints of 25, 42, and 60 µs. (Digitizer's first 11 bits or 46 mV are tested for linearity.)

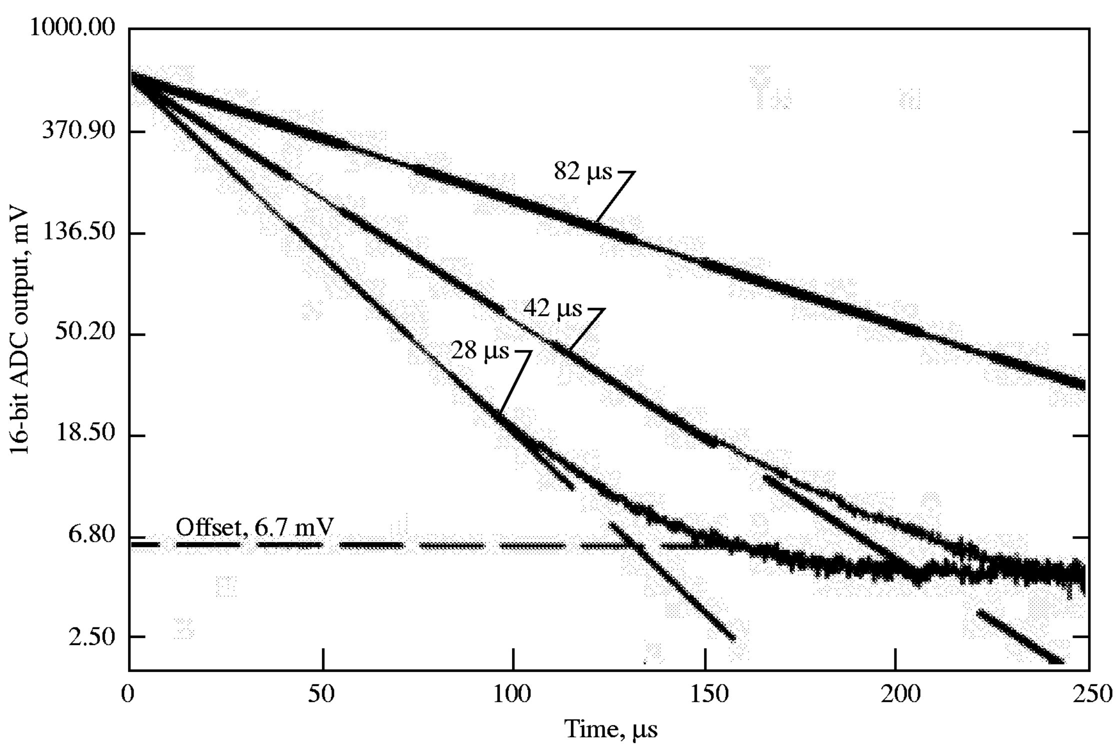


Figure 7. Digitizer linearity plots (natural log scale) using an arbitrary waveform generator with exponential time constraints of 28, 42, and 82 µs. Digitizer tested to 15 bits or 685 mV.

The atmospheric ozone density, as a function of altitude, is derived through the DIAL equation. Two laser pulses are emitted from the laser transmitter in the lidar system; one laser pulse is tuned to a strong atmospheric ozone absorption wavelength and the other to a weaker absorption in the ozone spectrum. The DIAL equation (eq. (1)) compares the decay of the two lidar returns generated from these two laser pulses. A difference in the decay of the two lidar returns indicates absorption of ozone in the atmosphere as a function of altitude.

$$\#\text{density} = \left[1/(2\Delta\sigma\Delta R)\ \ln(P_{\text{off(R2)}}P_{\text{on(R1)}}/P_{\text{off(R1)}}P_{\text{on(R2)}})\right] \quad (1)$$

where

$\Delta\sigma$ differential absorption cross section of ozone, 2.1×10^{-19} cm^2

σR range cell, 60 000 cm

P_{off} off-line lidar signal power

P_{on} on-line lidar signal power

Plots of an actual ozone lidar return obtained with the 16-bit digitizer system, standard ozone density in the atmosphere, and a DIAL calculation (eq. (1)) are shown in figure 8. The DIAL system was operated at a wavelength of 300 nm for both the on-line and off-line wavelengths, which should give zero ozone density as a function of altitude. Deviations from zero indicate the noise in the system. It is

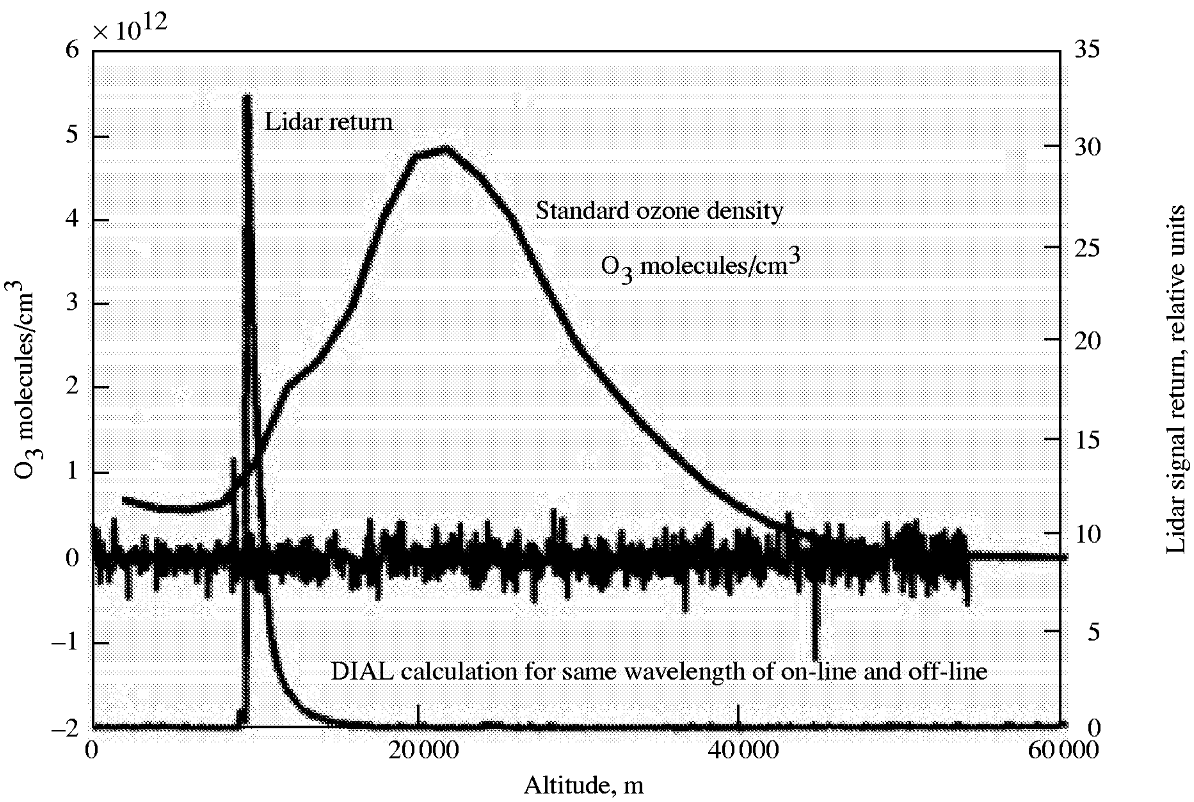
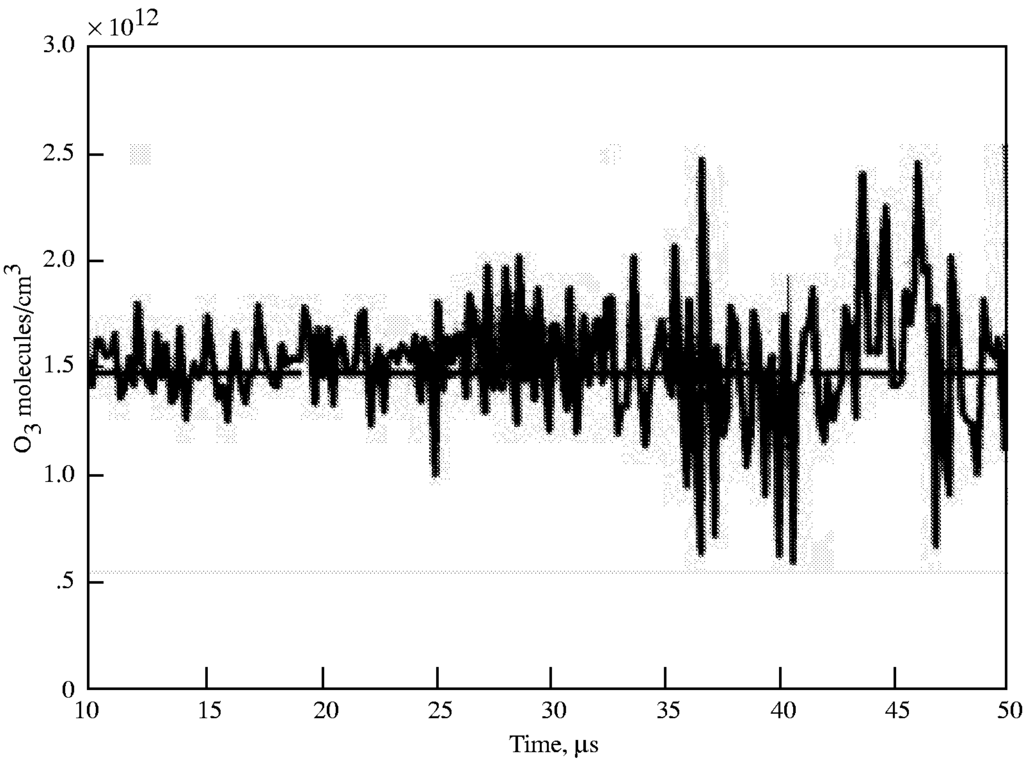
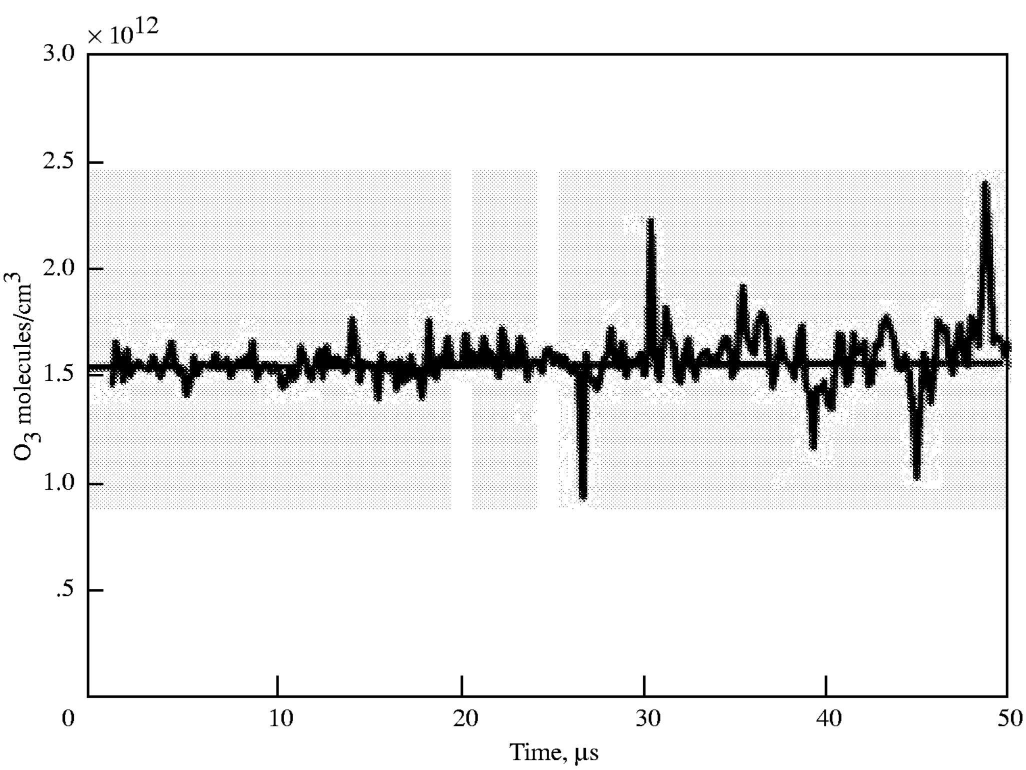


Figure 8. Actual ozone lidar return plotted where both on-line and off-line are at same wavelength, giving a zero ozone DIAL measurement. (DIAL calculation represents system noise compared to standard ozone density to be measured.)



(a) DIAL calculation for one trace, no averaging.



(b) DIAL calculation for 5000 traces, averaged.

Figure 9. Arbitrary function generator-created on- and off-line simulated lidar return; DIAL calculation resulted in simulated ozone concentration of 1.5×10^{12} ozone/cm^3.

shown in figure 8 that the digitizer and system noise are sufficiently low to resolve the expected stratospheric ozone density that is shown as the standard ozone density curve. Large noise spikes appear at the time the PMT gate opens and closes.

The DIAL calculation also was performed by using LabVIEW programming. The advantage of using LabVIEW is that the DIAL calculation could be incorporated into the main data acquisition program and thus be determined in near real time after the acquisition of the on-line and off-line lidar returns.

The DIAL calculation should be nonzero if the two pulses from the laser are at different wavelengths. An arbitrary function generator (fig. 2) was used to produce two exponential functions with different time constants, which simulated on-line and off-line lidar returns. The decay for the on-line and off-line lidar returns is not the same, which simulates ozone absorbance. The DIAL equation exploits this difference, producing a nonzero straight line corresponding to the differences in the time constants or ozone density. Discrepancies in the line are caused by noise in the instrumental system.

Figure 9(a) displays the DIAL calculations for two different exponential decays produced by the arbitrary function generator, with time constants of 37 μs (on-line) and 50 μs (off-line). The calculated simulated ozone density is 1.5×10^{12} molecules/cm^3, which is indicated with a dashed line in figures 9 and 10. This ozone density was estimated to be the center of the traces in figures 9 and 10. These data agree with results published by Langford for a comparable 12-bit digitizer system (ref. 3). Averaging 5000 traces (fig. 9(b)) improves the signal-to-noise ratio, which indicates that the large fluctuations are caused by random noise in the signal rather than by nonlinearities in the digitizer output. Figure 10

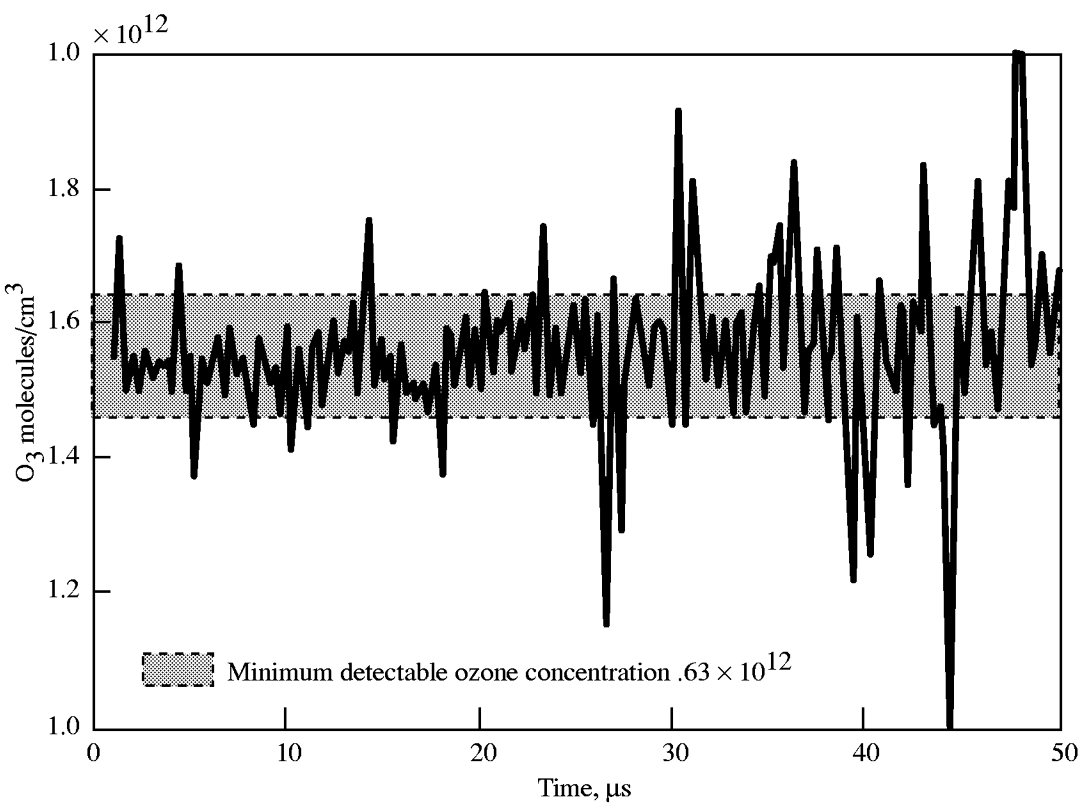


Figure 10. Assuming a signal-to-noise ratio of 2, the minimum detectable ozone concentration of 0.63×10^{12} ozone/cm^3 detected by using figure 9 configuration; 5000 traces, averaged.

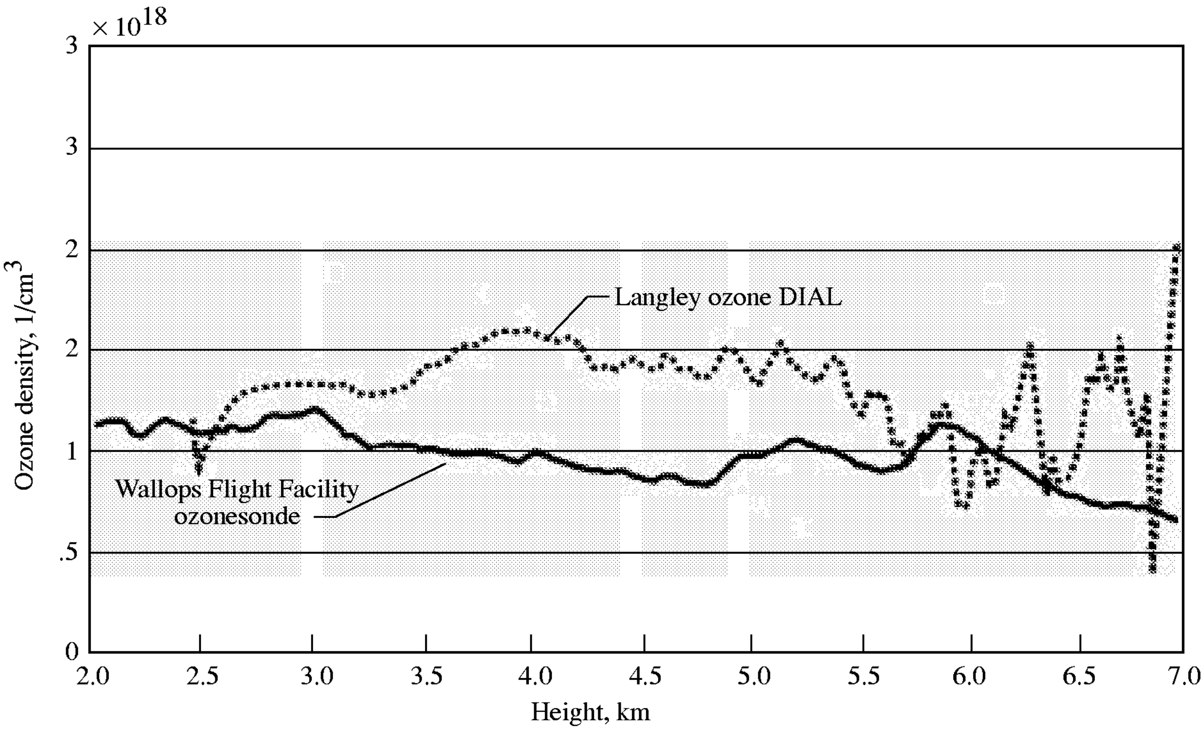


Figure 11. Assuming a signal-to-noise ratio of 2, the minimum detectable ozone concentration of 0.63×10^{12} ozone/cm^3 is detected by using figure 9 configuration.

displays the ozone density on a smaller scale, and a minimum detectable ozone concentration of 0.63×10^{12} molecules/cm^3, with a signal-to-noise ratio of 2, was derived from the trace.

A DIAL calculation of actual ozone lidar returns is shown in figure 11. The dotted trace was obtained at Langley Research Center, and the solid trace was obtained at Wallops Flight Facility by using an ozonesonde. The ozone density calculation is similar for the two locations, although they are 130 km apart. Differences in the ozone density are likely caused by slight changes in the ozone density at the different locations.

Concluding Remarks

A new 16-bit, 6-MHz compact, lightweight waveform digitizer module has been tested by using simulated and actual atmospheric ozone differential absorption lidar (DIAL) returns. The noise level of this digitizer was tested and found to be substantially below the ozone number density to be measured.

The digitizer is relatively inexpensive, lightweight (2.3 kg), and compact enough to be deployed in unpiloted atmospheric vehicles (UAV) aircraft and spacecraft environments. Also, the power requirement is only 2.8 W. With 16-bit digitizers, a resolution of 0.046 mV/step (based on V_{max} of 3.0 V) can be achieved, substantially improving voltage resolution over 12-bit systems. The linearity was tested and found to be sufficient over 15 bits. Further reduction in the noise level of the lidar system is necessary to implement the improved resolution of the 16-bit digitizer for greater sensitivity of lidar return signals. However, the enhanced resolution of the 16-bit digitizer results in greater sensitivity to changes in lidar signal magnitude above the baseline noise of the lidar system.

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A 6-MHz 16-bit waveform digitizer was evaluated for use in atmospheric differential absorption lidar (DIAL) measurements of ozone. The digitizer noise characteristics were evaluated, and actual ozone DIAL atmospheric returns were digitized. This digitizer could replace computer-automated measurement and control (CAMAC)-based commercial digitizers and improve voltage accuracy.

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