Design of control software for a high-speed coherent Doppler lidar system for CO_2 measurement

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ABSTRACT

The design of the software for a 2-micron coherent high-speed Doppler lidar system for CO_2 measurement at NASA Langley Research Center is discussed in this paper. The specific strategy and design topology to meet the requirements of the system are reviewed. In order to attain the high-speed digitization of the different types of signals to be sampled on multiple channels, a carefully planned design of the control software is imperative. Samples of digitized data from each channel and their roles in data analysis post processing are also presented. Several challenges of extremely-fast, high volume data acquisition are discussed. The software must check the validity of each lidar return as well as other monitoring channel data in real-time. For such high-speed data acquisition systems, the software is a key component that enables the entire scope of CO_2 measurement studies using commercially available system components.

Keywords: Coherent Lidar, Data Acquisition, Differential Absorption Lidar, Software, CO_2 Measurement

1. INTRODUCTION

Over the past decade or so, extensive research and development has been conducted by the NASA Langley Research Center to develop and mature high energy, pulsed, 2-micron laser technology. These lasers have been utilized in both Doppler Lidar [2-6,8,10-13] and Differential Absorption Lidar (DIAL) [7,9] configurations, using both direct and coherent (heterodyned) detection techniques.

Our current CO_2 Measurement Demonstration makes use of a high-speed coherent Doppler lidar[1] used previously for wind measurements. Three significant improvements have been made in the current transceiver compared to the system used in the ground demonstration in 2007. First, the system is now a 10 Hz, on-and-off pulse pair format transmitter, allowing improved measurement precision by sensing nearly the same atmospheric volume for both the on-line and off-line pulses, and effectively increasing the pulse repetition rate by four-fold. This will improve the measurement precision to better than 1.5% using 1000-m range bins, and reduce the required integration time to 2.112 minutes. Second, the selection of the R32 CO_2 absorption line over R22 further improves the measurement precision, due to its negligible water vapor line interference. The parameters of the R32 line are given with accuracy of 0.4% for the line strength, 0.15% for the air broadening coefficient, and 0.45% for the temperature parameter. These accuracies, together with the assumed accuracy of 2.6% for the pressure shift, are needed to attain the required CO_2 measurement precisions. Third, the laser power is eight times greater than that of the previous ground demonstration system. It will cover a larger measurement distance with increased signal carrier to noise ratio (CNR).

A major advantage of our current lidar is its ability to serve as a dual-use instrument - measuring atmospheric CO_2 concentrations as a coherent DIAL instrument, and 3D winds as a coherent Doppler lidar instrument. The capability to make such complementary measurements, coincident in space and time and with improved precisions and accuracies, is key to enabling future strategic atmospheric measurements, such as those called for in the NRC Decadal Surveys.

This paper will discuss various aspects related to the development of the Data Acquisition (DAQ) Software (SW) for the CO_2 Demonstration, and its operation and functionality; including hardware (HW) configuration, scanner operation, data acquisition, and minimal data processing and storage of the acquired signals. It should be stressed that this research effort - to show the feasibility of using an existing coherent Doppler lidar system to measure atmospheric CO_2 - was a technology demonstration, requiring quick modification and turnaround of the control software. Software development for *operational* science instruments, and especially flight instruments, is governed by NASA Procedural Requirements that ensure adherence to documented development processes.

This paper is organized as follows: the software development environment and the acquisition hardware are described briefly in Section 2. Section 3 provides an overview of the DAQ software and its user interface architecture, with its Validation Lidar (VALIDAR) heritage. Section 4 describes the acquired data and ways to assess the quality of each lidar return pulse. The last section provides conclusions as well as suggestions for future research and development of software for these dual use coherent lidar instruments.

2. THE ACQUISITION HARDWARE AND ENVIRONMENT

The data acquisition electronics were housed in an Agilent Technologies Acqiris CC105 Compact PCI (cPCI) Crate which provides five horizontal 6U slots. In the lowest "system" slot was a Single Board Computer (SBC) hosting a Microsoft Windows environment, allowing SW development and maintenance using the system itself.

We used two identical Agilent Acqiris DC-252 10-bit Series cPCI/PXI Digitizers cards. Each DC-252 was equipped with a mezzanine front-end card that provided standard (50 Ohms) impedance coupling through three BNC connectors: one for each of its two input channels, and another for an external trigger signal. Internal triggering is also supported, using the signal level on one of the input channels. Both of our DC-252 cards were equipped with the maximum optional memory, accommodating up to 256M samples per channel. While it may be tempting to install electronics cards in alternate slots for thermal reasons, the DC-252 cards were placed in the two adjacent slots just above the system slot to minimize potential communications delays.

The DC-252 digitizers support a large number of configurations for different data acquisition requirements. For example, both Channel 1 and Channel 2 have their own A/D converter (ADC) and acquisition memory, but the ADCs can be "interleaved" and the acquisition memory combined to support a single channel with more capability. In addition, the acquisition memory is dual-ported and can be configured as a circular buffer to allow for Simultaneous Acquisition and Readout (SAR) operation. These advanced features were not required for the current demonstration project, but may be useful for future enhancements.

In our configuration, the two DC-252 Digitizers were connected together using an external AS bus 2 connector. The Acqiris System Software configures the two identical dual-channel digitizers into a single "Multi-Instrument" with four input channels, and which share a common internal clock and external trigger. We used one input channel (Channel 1) of each DC-252 card. Note that for the 4-channel Multi-Instrument, the system software renumbers the channels, and they are henceforth referred to as Channel 1 and Channel 3.

The Acqiris System Software Application Programming Interface (API) is described in a variety of documents such as a Programmer's References Manual[14] and a User Manual[15] for the 10-bit digitizer family. Some API procedures are specific to the 10-bit series while others are applicable to different models. In some cases different models use the same procedures but interpret the parameters passed to them differently. It is essential that the software developer read the documentation thoroughly.

CO_2 measurements require very large amounts amount of data to be acquired in a short time. It was thus necessary to test the HW to ensure that it could accommodate these sample frequencies and data volumes, without dropping a pulse. The DC-252 digitizers store each triggered pulse in its own "segment" of acquisition memory, along with a Segment Descriptor - a data structure containing timing and auxiliary information. Each Segment Descriptor includes two 32-bit unsigned integer variables, *timeStampHi* and *timeStampLo*, that record the pulse's start time in picoseconds. As a stress test, we acquired 75,000 samples at 500 MHz for each of 200 pulses fired at 5 kHz, corresponding to 200 μs or 200,000,000 ps between pulses. If no pulses were missed, the timestamps between the first and last pulse should differ by about 199 * 200 μs = 39,800 μs. The segment descriptors for the first and last pulses showed the following:

	segDesc[0]		segDesc[199]	
timeStampHi	5972	*timeStampHi*	5982	
timeStampLo	3615426219	*timeStampLo*	465744444	

The less significant *timeStampLo* "rolls over" at 2^{32} ps, incrementing *timeStampHi* in the process. Thus, the first and last times stamps are equivalent to 25,653,160,117,931 ps and 25,692,960,109,116 ps, respectively, and differ by 39,799.991185 μs. This indicates that the digitizer captured all of the pulses, even at a 5 kHz pulse rate and while collecting 75,000 samples per pulse.

3. DESIGN AND DEVELOPMENT OF CO_2 MEASUREMENT SOFTWARE

We developed the Data Acquisition (DAQ) Software to support this Coherent Lidar CO_2 Measurement Demonstration by modifying the existing VALIDAR application written in 2007 by the second author of this paper. The VALIDAR SW was developed using Visual C++ 6.0. The Graphical User Interface (GUI) was built within Microsoft Visual Studio, and made use of National Instruments Measurement Studio for graphical displays (Figure 1).
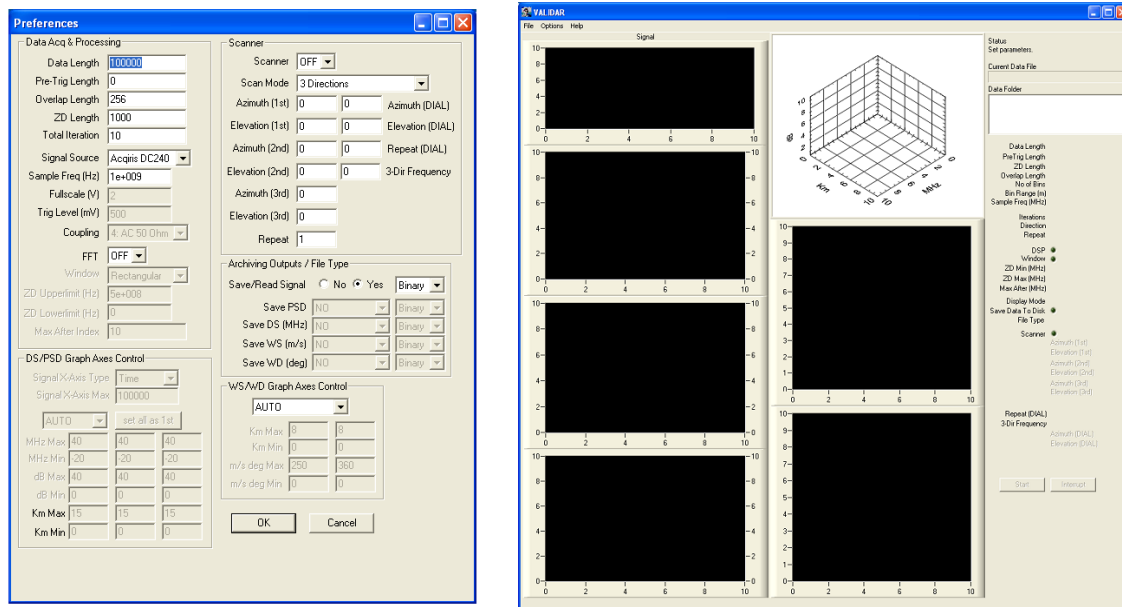

Fig. 1. The Original VALIDAR Preferences Dialog and Run-Time Display

We opted to use the same tools and versions used to develop the VALIDAR SW for several reasons. 1) This precluded some potential problems, such as compiler inconsistencies. 2) The CO_2 and Doppler wind measurements - while different in nature - used essentially the same laser equipment, allowing reuse of the scanner control software without modification. 3) Our CO_2 Demo used new digitizer HW, but it was from the same vendor and the software interfaces were very similar. Finally, we hoped to facilitate future development of SW to acquire both types of measurements.

There were also some challenges presented by these choices. The VALIDAR SW included DAQ, but also Data Analysis and Processing (DAP) functionality - which was relegated to post-processing for the CO_2 Demo. Also, a significant fraction of VALIDAR code implemented its User Interface, and modifications to this code were not straightforward.

The architecture of the CO_2 Demo SW was built around the two VALIDAR Windows Dialogs (Figure 1), implemented as Visual C++ classes. User settings for a data acquisition are read from an ASCII preferences file, displayed in the Preferences Dialog (left) where they can be modified, then re-saved to the ASCII file. When the OK button on the Preferences Dialog is clicked, the Main Dialog (right) is enabled for data acquisition.

We initially planned to modify the VALIDAR SW and GUI, but retain all of its Doppler wind features. However, the current software developer was not familiar with the internals of the VALIDAR C++ code. To make the amount of code manageable for understanding and modification within the short deadline, it became necessary to temporarily strip out the unused Doppler code and interface elements.

4. DATA ACQUISITION AND ANALYSIS

For the CO_2 Demonstration, we acquired data using the following parameters:
- Sampling Frequency   500 MHz
- Samples per Pulse   17,500
- Pulses per Set/File   600
- Pulse Frequency   10 Hz

The digitizer HW was configured to simultaneously acquire data on two channels. The data acquired for two consecutive pulses are displayed in Figure 2, with Channel 1 in the top graph and Channel 3 in the bottom graph. The first 1024 samples of each pulse are called the *Monitor Region* and the remaining samples the (Atmospheric) *Return Region*. (For Doppler wind measurements the Monitor Region is referred to as the Zero Doppler (ZD) Region.)
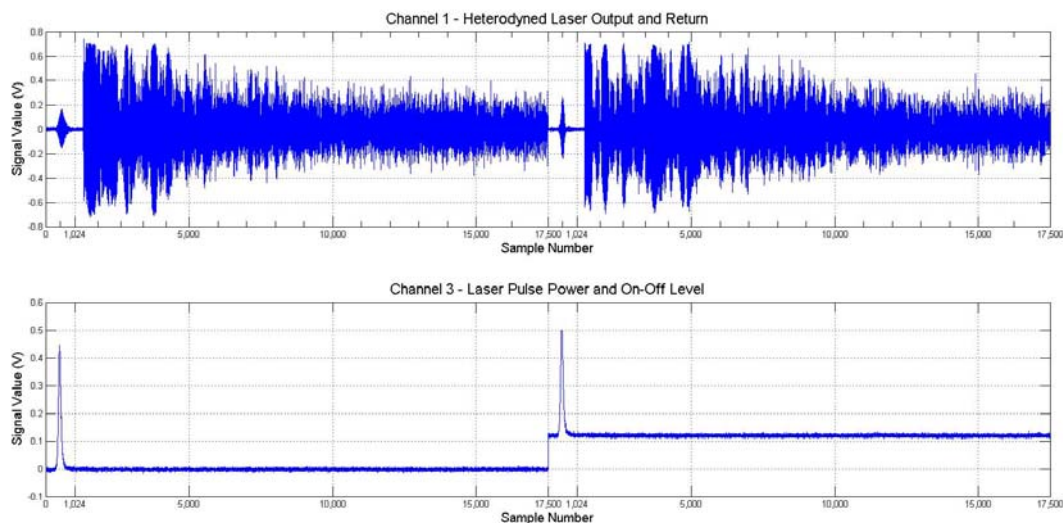

Fig. 2. Two consecutive pulses showing acquired data from both Channel 1 (heterodyned lidar pulse, outgoing and atmospheric return) and Channel 3 (pulse represents outgoing lidar pulse power, base signal represents input to switch multiplexing on-line and off-line frequencies). For this CO_2 Demo the laser was pulsed at 10 Hz, and 17,500 samples acquired at 500 MHz for each. The first pulse is at the on-line frequency and the second at the off-line frequency.

The Monitor Regions of both channels are expanded in Figure 3. The first pulse was at the on-line frequency of the DIAL instrument and the second at the off-line frequency. (Note that *on-line* denotes a frequency selected within the R32 CO_2 absorption line, while *off-line* denotes one selected nearby - but well outside the absorption line. The *on-line* frequency may coincide with the center frequency of the absorption line, but more often is slightly displaced from the

center at a *side-line* frequency.) By taking an FFT (Figure 4) of the Channel 1 Monitor Region, and finding the peak frequency, one can determine the quality of each pulse. In our experiment, a pulse was deemed *Good* if the peak frequency was within 5 MHz of the average frequency, which was about 109 MHz. In one session we collected 30 sets of 600 pulses each (18,000 pulses) while observing only 14 *Bad* pulses.
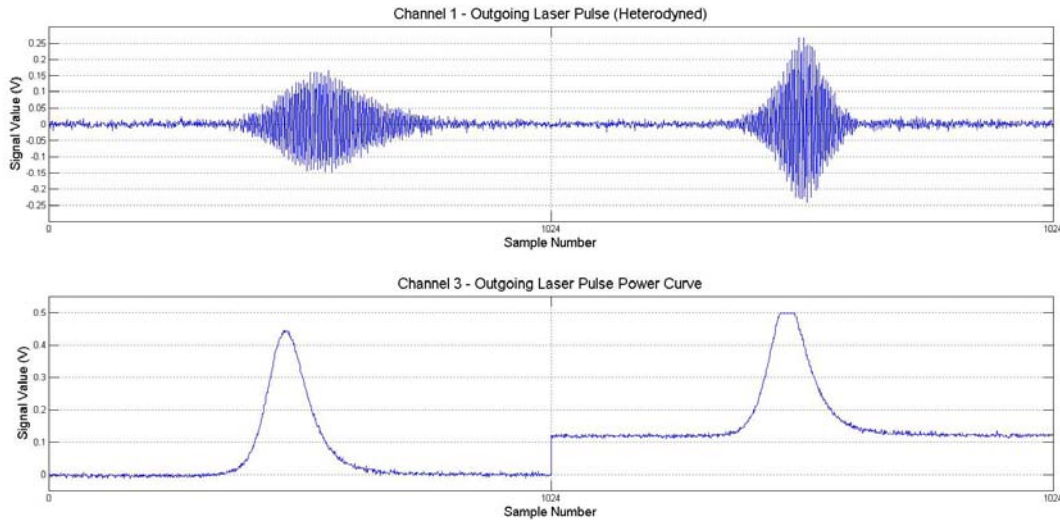

Fig. 3. Expanded view of the Monitor Region for the same two pulses as in Figure 2. The Channel 1 monitor data (top) provides frequency spectrum information for the corresponding lidar pulse as it is emitted. This is used to identify Good vs. Bad pulses, and also to quantify residual jitter between the frequencies of the seed laser signal and the actual lidar pulse. The base signal level in the Channel 3 monitor region (bottom) indicates whether the pulse frequency is on-line or off-line. (On-line is indicated by the lower level, near 0.0V.) The area under the peak can be integrated to determine total pulse power. Note the slight saturation of the second pulse where the Channel 3 data are truncated at about 0.5V. This is easily corrected using the Acqiris System Software to adjust the offset for that digitizer channel.

The VALIDAR program implements both DAQ and DAP Tasks. For the CO_2 Demo, DAP was delegated to post-processing using separate software. However, we prototyped some of the CO_2 DAP SW in MATLAB, pending additional resources to develop more formal versions.

While the CO_2 Demo was restricted to DAQ SW, some DAP SW functionality is useful to determine the quality and characteristics of each lidar return pulse during operations. This information can facilitate decisions related to where to take subsequent data and what acquisition settings to change. In addition, while pulses nominally alternate between on-line and off-line frequencies, occasionally 2 or 3 adjacent on-line pulses are observed. Thus it is always necessary to determine the frequency of each pulse. This is easily done by examining the base voltage of the Channel 3 signal, which is very close to 0.0V for on-line pulses and about 1.2V for off-line pulses.

The Channel 3 base voltage is measured in the Return Region near the center of the pulse. Once this value is determined, the remainder of the Channel 3 Return Region is redundant and need not be saved to a file. Also, one might opt to save only Good pulses, as described above. Thus, the use of some rudimentary DAP SW during data acquisition can decrease the data transfer and storage overhead.
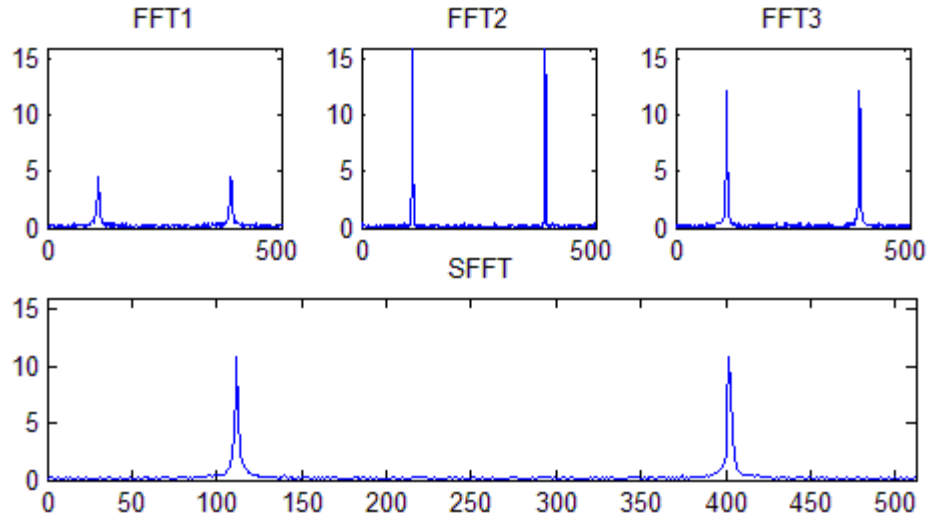
Fig. 4. Magnitudes of 50% overlapping, 512-element FFTs (top row) of the Monitor Region of Shot #1, Channel 1. These are combined to get an average (bottom row) FFT. The peak frequency (at index 112 here, corresponding to about 109 MHz) is used to determine if the return data is to be considered *Good* and further processed, or *Bad* and discarded.

5. CONCLUSIONS

DAQ SW was rapidly prototyped to demonstrate the ability to make very high frequency atmospheric CO_2 measurements using a coherent DIAL lidar instrument previously used for coherent Doppler wind measurements. This CO2 Measurement Demonstration showed that the HW and SW could satisfy the challenging requirements related to sampling frequency and data storage for this application. There are additional techniques and digitizer configurations that could accommodate future, more taxing requirements.

It may be beneficial to develop DAQ SW for such dual-use lidars, especially if there is an anticipated need to support future space-borne versions of these instrument. While the DAP SW may be separately developed for post-processing, some DAP functionality is required during acquisition to provide quick-look display information, and to determine the quality of each return pulse. By filtering the data based on quality and retaining only what is acceptable, the challenging requirements for data storage and transfer posed by these instruments can be mitigated.

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