Ultrahigh Dynamic Range Digitizer/Counter for LIDAR

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Abstract – We describe a method we call the Hybrid Digitizer (HD) for extending the dynamic range of a high-speed analog-to-digital converter (ADC) by as much as several orders of magnitude compared to existing technology. Through high-speed data transfer, programmable signal processing, and signal gain control, a transient ADC digitizer can be operated in a single-photon detection mode while simultaneously detecting strong signal in the normal manner. In-field testing was conducted on an atmospheric Lidar system and on a laboratory time-of-flight mass spectrometer (TOFMS) system. The HD method demonstrated data quality and dynamic range matching the combined response of the ADC and pulse counting systems. For airborne remote sensing, the HD technology provides greatly increased capability as well as enabling more compact design and a reduced cost.

I. INTRODUCTION

There is a critical need to develop electronic detection systems capable of recording high-speed transient events. One of the major challenges in high-speed digitization is maximizing the dynamic range of detection, which we define as the measurable range spanning the limit of weak to strong signal. In this paper, we describe a new method for extending the dynamic range of a high-speed analog-to-digital converter (ADC) by as much as several orders of magnitude compared to existing technology. It makes use of commercially-available ADC boards that have on-board memory and the capability to record single-shot transient events; we call the resulting device a transient digitizer (TD). It is especially effective for recording non-repetitive transients, in which each transient has slightly different shape.

The method for extending the dynamic range of high-speed ADCs is based on an algorithm that enables a transient digitizer to operate in a pulse-detection mode simultaneous with detection of strong signal. A schematic showing the principal functional components of the invention, which we call a hybrid digitizer (HD), is given in Figure 1. Transient waveforms are digitized by a conventional ADC and the data passed onto a fast data bus. An input stage consisting of pulse shaping or filtering electronics for example may be used. The data from the bus are then processed according to the algorithm outlined in Figure 1. The processed data are then placed in memory and summed or averaged to give a final spectrum. The processing may be done in real-time as the data are coming in or the entire data stream may be stored and post-processed later. The processor and sum/averager may reside after the data bus as shown in Figure 1 or on the ADC board directly. The latter method leads to faster processing by avoiding the data transfer speed restrictions.

The benefits of the HD are represented in Figure 2. For simplicity, we illustrate the use of an 8-bit digitizer. We use as examples of applications the detection of ions such as for time-of-flight mass spectrometry (TOFMS) and the detection of photons such as for light detection and ranging (LIDAR). The minimum signal level detectable by a transient digi-

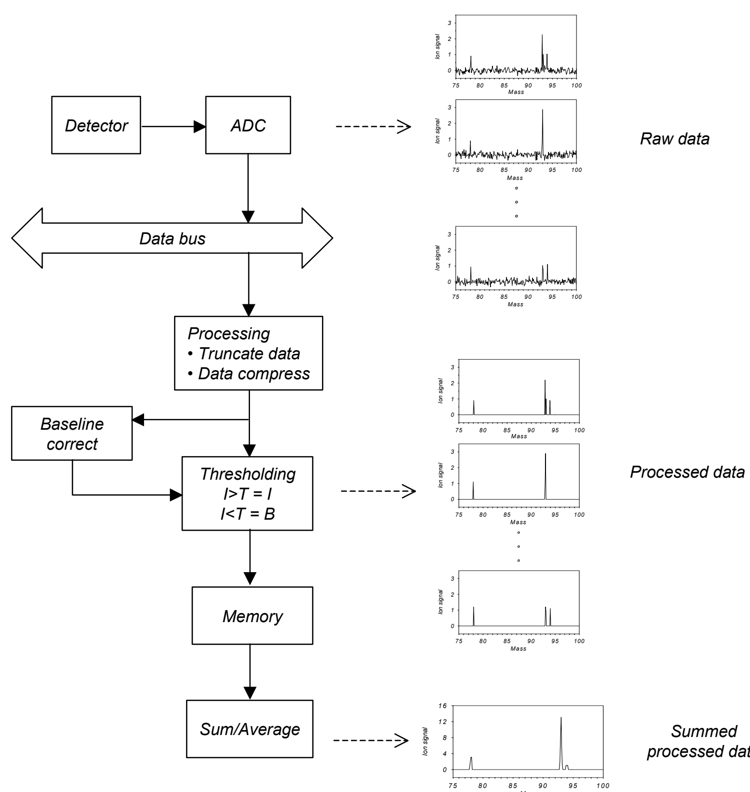

Figure 1. Flow diagram describing the components and operation of the hybrid digitizer.

Table I.
SIGNAL RECOGNITION LOGIC FOR HD AND OTHER DATA ACQUISITION METHODS

Logic condition	Conventional digitizer	Conventional MCS	Hybrid digitizer	Threshold digitizer	Offsetting digitizer
$I \geq T$	I	1	I	I	I
$I < T$	Noise level	0	B	0	T

B = baseline

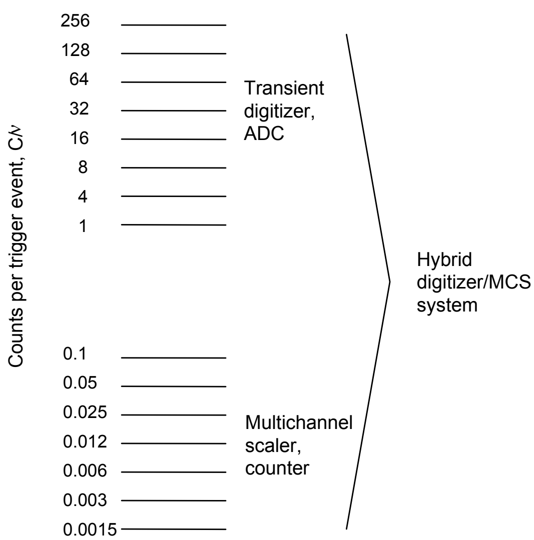

Figure 2. Operating range of the hybrid digitizer.

tizer is generally on the order of one ion or photon per time bin per trigger event, depending on analog noise being sufficiently low. Transient digitizers are considered to operate in what is called the strong signal limit, usually defined as a detected flux of ions or photons corresponding to multiple events per time resolution element (or time bin). Weaker signals are generally masked by the summed analog noise arising from the detector, amplifier, and digitizer.

The weak signal regime is defined as the detection of less than one ion or photon count per bin per trigger event. In this regime, it is necessary to use pulse detection for individual ion or photon counts, where each pulse is timed and deposited as a bit in a time bin measured by a multichannel scaler (MCS). To achieve high-speed operation, pulses are detected as binary events, returning either a 0 or 1. This leads to the potential for counting error when multiple pulses are detected as one pulse. To keep the probability of multiple pulses per time bin per trigger event to an acceptable level, the maximum counting probability per time bin is typically limited to about 0.1. Table I summarizes the logic conditions for conventional transient digitizer and MCS/averagers and the hybrid digitizer disclosed here.

High dynamic range applications often use both transient digitizer and MCS/averager systems. However, this method has several drawbacks: (1) such a system is expensive and complicated, (2) it requires routines to recognize whether a signal is in the strong or weak limit, (3) it must seam the data together from the two detection systems, and (4) the regime where signal lies between 0.1 and 1 count per trigger event per bin is inadequately measured by either method.

Methods similar to the invention here have been used, however, they have basic deficiencies that are solved in this invention. These are summarized in Table I and illustrated in Figure 3. One method uses a threshold condition for a digitizer (threshold digitizer) similar to that disclosed here. However, the routine does not keep track of the baseline value and hence intensity errors can occur as illustrated in Figure 3. Another method is also based on a transient digitizer and achieves noise elimination by offsetting the signal so that the analog noise appears below the mini-

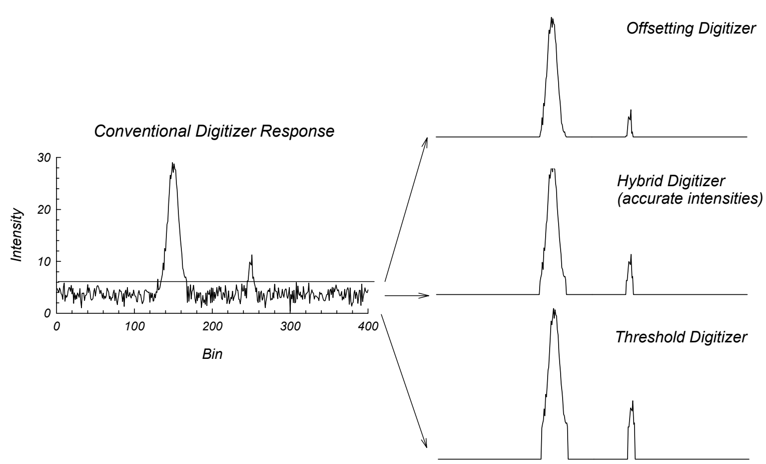

Figure 3. Comparison of different ways to apply a threshold to a TOF ion signal. This example shows that only the HD method gives true relative intensities.

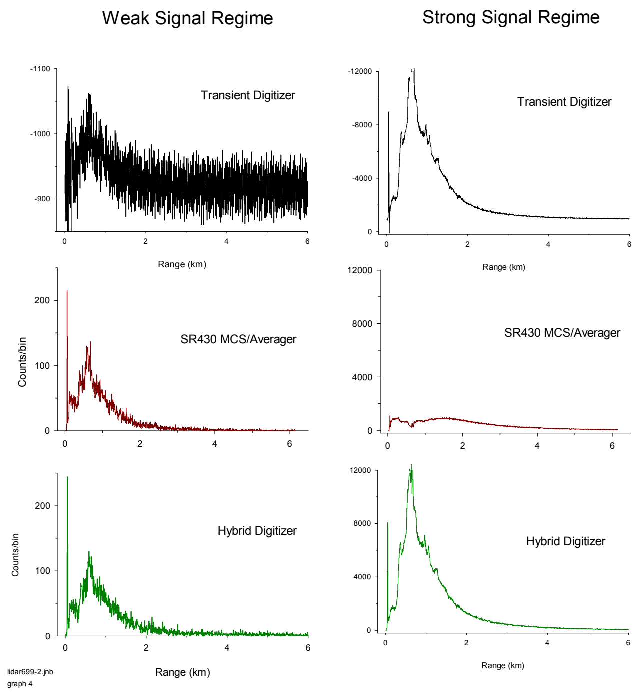

Figure 4. Comparison of HD to MCS/scaler and to transient digitizer detection systems.

mum scale (offsetting digitizer). The minimum scale then defines the threshold for signal and the minimum value. Again, the true baseline is not recorded and intensity errors can result as illustrated in Figure 3. The hybrid digitizer, by comparison, tracks the baseline value and uses it for the low-level logic condition as noted in Table I. This algorithm leads to accurate relative intensity measurements.

II. Lidar

Figure 4 compares the HD to conventional MCS and transient digitizer for Lidar return signal in the weak and strong signal regimes. The HD is validated in weak & strong signal regimes. The following summarizes the observations:

Weak Signal Regime: The summed transient digitizer analog noise overwhelms the weak photon count signal. The MCS/averager correctly measures the return signal. The HD gives essentially an identical response to the MCS/averager.

Strong Signal Regime: The transient digitizer correctly measures the return signal (except for the long range DC offset). The MCS/averager saturates severely in this regime. The HD gives essentially the same response as the transient digitizer, while also removing the distorting DC offset at long range for the transient digitizer.

III. TOFMS

The HD technology is well suited to other time-of-flight applications relevant to NASA missions. In particular we have tested the technology on time-of-flight mass spectrometry (TOFMS), which is an area of R&D and commercial development at Syagen. This application is very demanding because of the very high sampling rates (1 GS/s) and long record lengths (typically >30,000 pts). In many ways this is a more stringent test than Lidar because of the much higher digitizing speeds and record lengths needed. However, it generally only needs one channel of detection, which eases the total data throughput requirement.

An HD system based on the high-speed PCI bus was tested on a TOFMS system. The principal result was

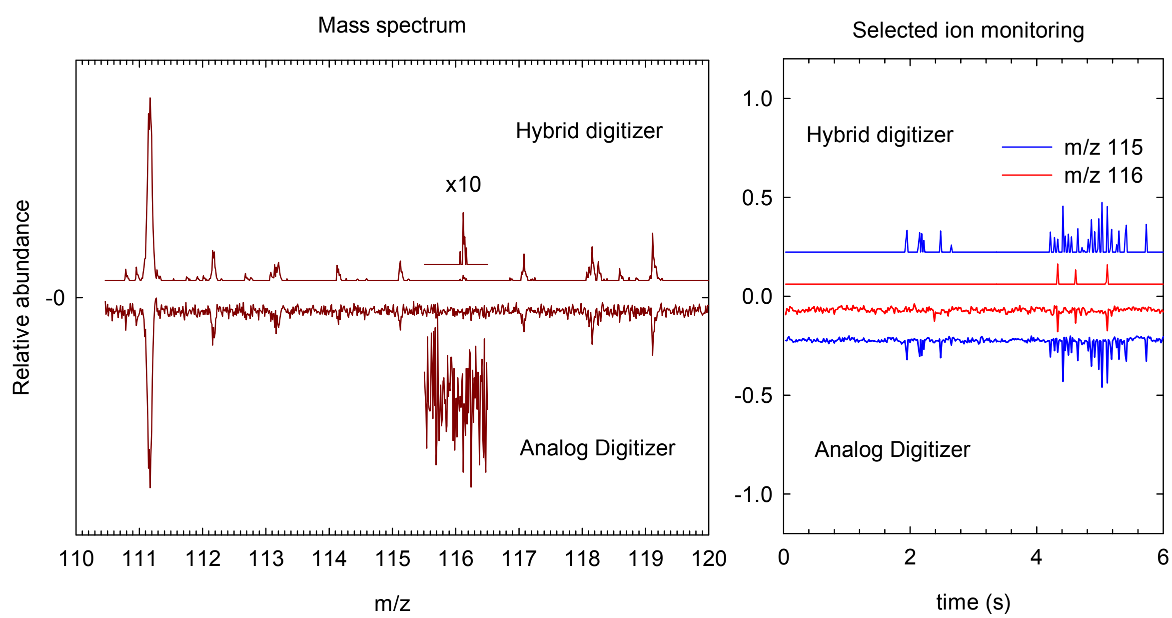

Figure 5. (left) Comparison of summed TOFMS spectrum recorded using conventional analog digitization and hybrid digitization. The right hand plot shows the time profile for selected masses. Note that the m/z 116 signal consists of only three ion counts.

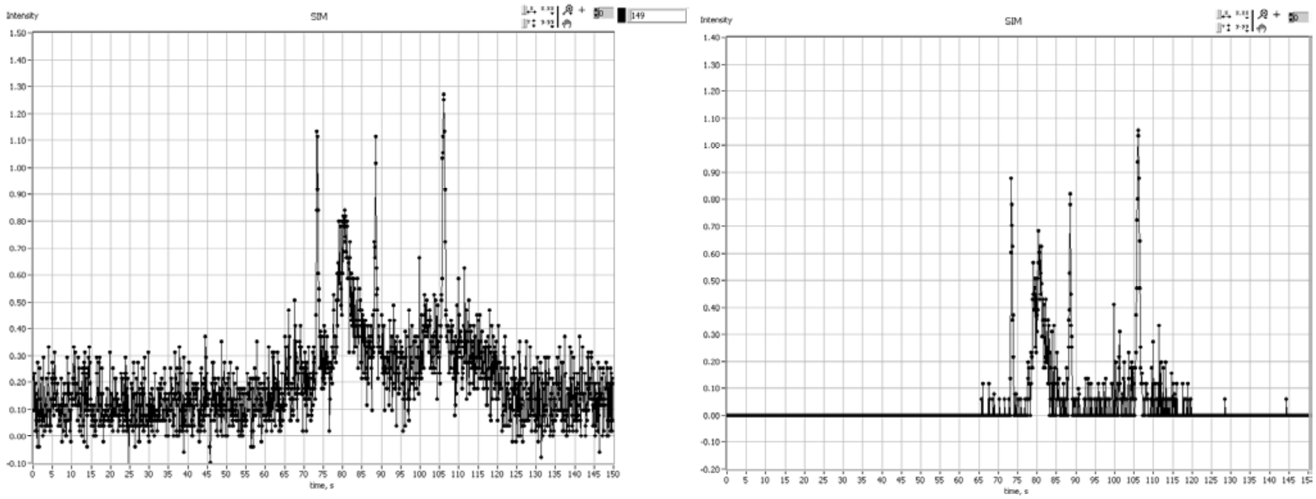

Figure 6. Conventional (left) vs. hybrid digitizer (right) for selected ion monitoring by GC/TOFMS.

the demonstration that single counts (ions in this case) could be picked out of analog noise. In effect the HD is acting as a counter, but also faithfully reproducing strong signal. Figure 5 demonstrates the expected performance of the HD showing an improvement in signal-to-noise of about 100.

Another example of the benefits of HD for TOFMS applications is in the measurement of selected ion monitoring peaks for chromatographic separations. Figure 6 shows an example of very weak signal corresponding to ion mass detection of compounds eluting from a gas chromatographic column. The use of the thresholding condition of HD filters analog noise from real signal including single ion count signal. The comparison between conventional digitizer and hybrid digitizer highlights the success in removing noise and improving signal-to-noise.

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