PRECISE DIGITAL INTEGRATION OF FAST ANALOGUE SIGNALS USING A 12-BIT OSCILLOSCOPE

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Abstract

An accurate laboratory characterization of beam intensity monitors requires a reliable integration of analogue signals simulating beam pulses. This poses particular difficulties when a high integration resolution is necessary for short pulses. However, the recent availability of fast 12-bit oscilloscopes now makes it possible to perform precise digital integration of nanosecond pulses using such instruments. This paper describes the methods and results of laboratory charge measurements performed at CERN using a 12-bit oscilloscope with 1 GHz analogue bandwidth and 2.5 GS/s sampling.

INTRODUCTION

The study of using 12-bit oscilloscopes as a high resolution digitiser has been considered for a laboratory characterisation of new intensity monitors currently being developed for the LHC restart in 2015 [1]. These monitors, operating according to the current transformer principle, provide signals proportional to the beam current, which are then integrated to measure the charge of each bunch of the circulating beam. Precise laboratory characterisation of such monitors requires time domain integration of nanosecond pulses with a relative accuracy better than 1 %. This value is considered as the accuracy limit of the analogue integrators used operationally at the LHC. The analogue integrators will be soon replaced by a digital system being developed, however, which was not yet available for the laboratory measurements of the new intensity monitors.

The study and results presented in this paper are based on oscilloscope measurements of nanosecond pulses from a fast pulse generator. Therefore, they are believed to be applicable also in domains outside the beam intensity instrumentation, where measurements of precise integrals of short pulses are necessary.

SET-UP AND OSCILOSCOPE

The pulses simulating beam bunches in the measurements discussed in this paper were generated by a custom-made avalanche generator delivering pulses with the amplitude of about 25 V and 0.5 ns full-width-at-half-maximum (FWHM) [2]. The pulse rise and fall times are about 0.3 ns, resulting in the frequency spectrum with the high cut-off around 1 GHz. Longer pulses required in the measurements were obtained by stretching the 0.5 ns pulses using a few commercial low pass filters. This way the total integral of the pulses, simulating the charge of a circulating bunch, was kept constant while the shapes of the pulses varied significantly.

All data studied in this paper were acquired using a 12-bit oscilloscope with 1 GHz analogue bandwidth and running in the Random Interleaved Sampling (RIS) mode with the maximal equivalent sampling rate of 125 GS/s. In this mode, the final waveform is a result of many acquisitions performed with the sampling clock having a random phase with respect to a common stable trigger. The phase of the sampling clock is measured with respect to the trigger for each acquisition by a precise time-to-digital converter (TDC), with the time resolution defining the RIS equivalent sampling rate. Then all RIS records are aligned according to the precise sampling phase measurement obtained from the TDC. The RIS scheme requires that the sampled signal is repetitive and the trigger event is identical for every acquisition, both of which conditions were satisfied in the discussed measurements. The RIS mode allowed increasing the oscilloscope native time resolution of 400 ps by a factor of 50, which was very important for the presented studies.

Before using the oscilloscope for signal integration, the instrument itself was characterised. In order to check the oscilloscope channel symmetry, the same signal from the avalanche generator was successively injected into each of the four inputs and sampled in the same manner. The absence of RF signal splitters in the measurement setup removed sources of systematic errors introduced by the inevitable asymmetry of the splitters themselves, which is at the percent level even for precise devices.

Results of the symmetry measurement are shown in Fig. 1. The measurements were performed consecutively assuring stable measurement conditions. The acquired samples were manually aligned on the time axis to

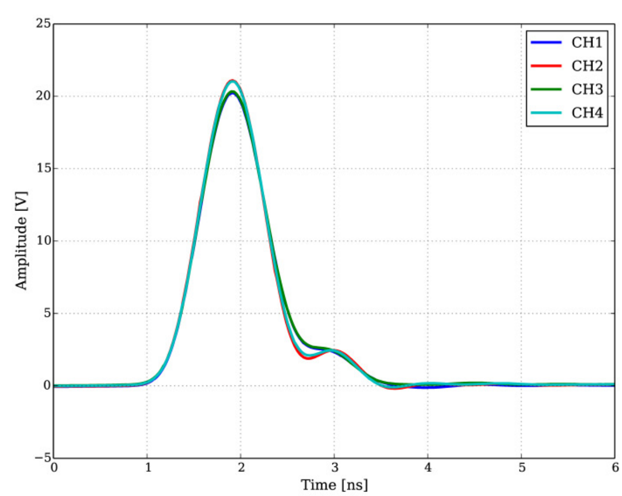

Figure 1: Measurement of the oscilloscope channel symmetry. Same input signal was acquired with consecutive channels.

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achieve the best signal overlapping. Nevertheless, significant discrepancies between the oscilloscope channels can be observed. In particular, channels are more symmetric in pairs 1 and 3 as well as 2 and 4, than in other combinations. The differences between the channels are shown in Fig. 2. The vertical axis denotes the relative difference between the channels scaled to the pulse amplitude. Both offset and gain asymmetry of the channels are visible. While the offset error (below 0.5% of the full scale, FS) can be easily corrected by measuring its value with no input signal, the only way to correct the gain error (up to 5% FS for the "more asymmetric channels") is to use a calibration reference with a well-known and stable amplitude.

The difference between the high-resolution 12-bit instrument used for the measurements described in this paper and an "ordinary" 8-bit oscilloscope is illustrated in Fig. 3. The 8-bit samples are simulated by taking the original 12-bit samples and clearing their 4 least significant bits. The resolution improvement offered by the 12-bit oscilloscope is very significant and probably opens a new era in laboratory oscilloscope measurements.

Please note that the 1 GHz bandwidth of the used oscilloscope results in its rise time of about 0.3 ns, the same as the rise time of the fastest pulses used in the discussed measurements. This modifies the shapes of the recorded pulses but does not influence the drawn conclusions based always on relative measurements.

INTEGRATION

The different pulses used to study the digital integration are shown in Fig. 4. Due to its large amplitude, the generator output signal was attenuated by 43 dB with 18 GHz attenuators, lowering it to the level representative for intensity monitor characterisation. Whenever applicable, the presented plots are corrected to take into account this attenuation, like in Fig. 4. The 0.8 ns pulse is the direct pulse from the avalanche generator while the remaining 5 pulses were obtained by low-pass filtering of the 0.8 ns pulse.

In order to improve the quality of the integrated signals, the generator pulses were averaged 400 times using the oscilloscope internal averaging prior to undergo digital integration. After some attempts of using the oscilloscope built-in option of calculating signal integrals, this idea was abandoned due to its limited accuracy, most likely due to the lack of a proper offset suppression. All presented integration was performed as a post-processing of the acquired signal records, with particular attention on the accurate correction of the oscilloscope offset errors.

In order to optimally use the oscilloscope ADC, the vertical sensitivity of the instrument was set to utilise at least 50 % of the available dynamic range in all the following integral measurements. This is why the 0.8, 1.2 and 1.5 ns pulses were measured with the scope gain set to 160 mV full scale, while the remaining 2.1, 2.5 and 3.4 ns pulses with the full scale of 80 mV.

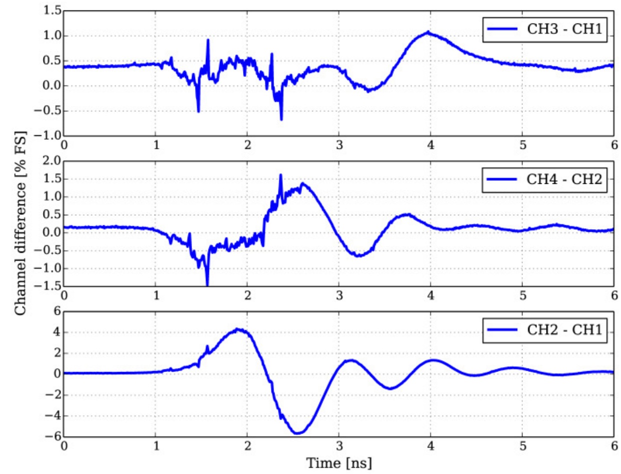

Figure 2: Measurement of oscilloscope channel symmetry. Shown are relative differences of the waveforms of Fig. 1.

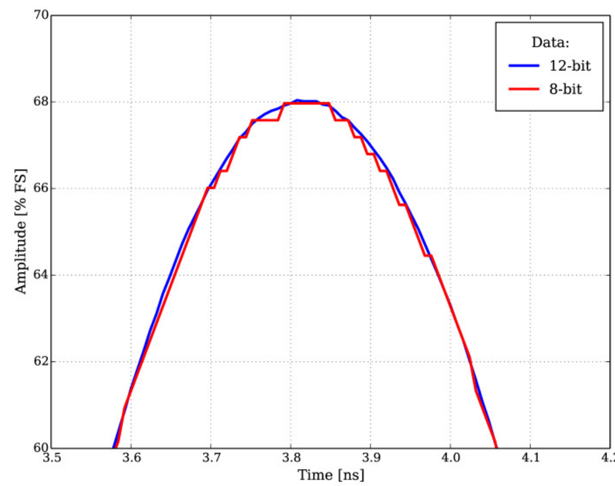

Figure 3: Comparison of the same signal with 12-bit and 8-bit resolution, zoom on the top of the pulse.

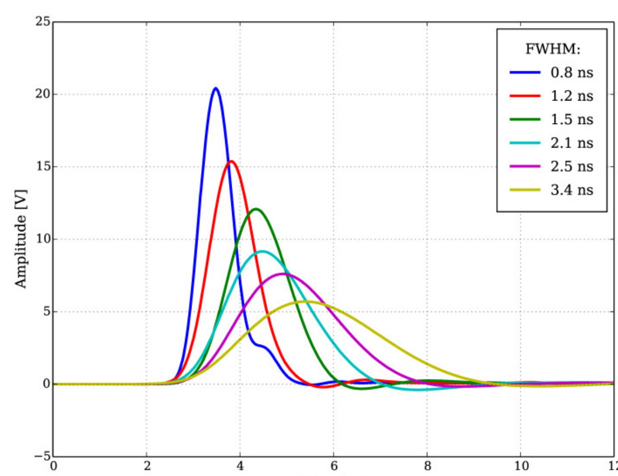

Figure 4: Pulses undergoing digital integration. The 0.8 ns pulse comes directly from the avalanche generator and the other pulses were produced using low-pass filters.

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Table 1: Relative Difference Between the Integrals of the Native 12-bit Records and their 8-bit Equivalents

Pulse FWHM [ns]	**Used filter [MHz]**	**ADC usage [% FS]**	**Integral difference [%]**
0.8	**none**	90.8	2.9
1.2	470	68.8	3.6
1.5	300	54.7	3.9
2.1	200	84.7	3.1
2.5	155	68.8	3.0
3.4	120	51.8	2.7

Table 2: Effect of the Sampling Rate and the Integration Method for the 3.4 ns Pulse

Sampling rate [GS/s]	**12-bit integration error [%]**		**8-bit integration error [%]**	
	trapez	**rectangle**	**trapez**	**rectangle**
125	**reference**	0.00	2.7	2.7
64	0.01	0.01	2.7	2.7
16	0.07	0.07	2.7	2.7
4	0.08	0.09	2.7	2.7
1	0.14	0.17	2.6	2.6
0.5	0.87	0.71	2.8	2.8

For each measurement 12500 samples were recorded over a time window of 100 ns with the resolution of 8 ps. The samples of the first 10 ns preceding the actual pulse were used in the post-processing as a reference for offset suppression. All the integral measurements were performed with the same oscilloscope channel.

Three main contributors to the accuracy of a digital integral were studied, with the results described in this chapter, namely the ADC resolution, the sampling rate and the used integration algorithm.

To study the effect of the ADC resolution each signal was acquired and integrated using the trapezoidal method. Then from these records acquired with the native 12-bit resolution their 8-bit equivalents were produced, by clearing the 4 least significant bits, and such 8-bit records were also integrated. Table 1 summarises the obtained integral relative differences. The table also lists the cut-off frequency of the low-pass filter used to stretch the integrated pulse and the usage of the ADC dynamic range. The ADC usage was calculated as the ratio of the peak-to-peak signal amplitude to the full scale of the oscilloscope for the vertical gain used in the measurement.

The difference between the 12-bit and 8-bit integrals varies between 2.7 and 3.9 %. For the three shorter pulses the decreasing usage of the ADC seems to be the source

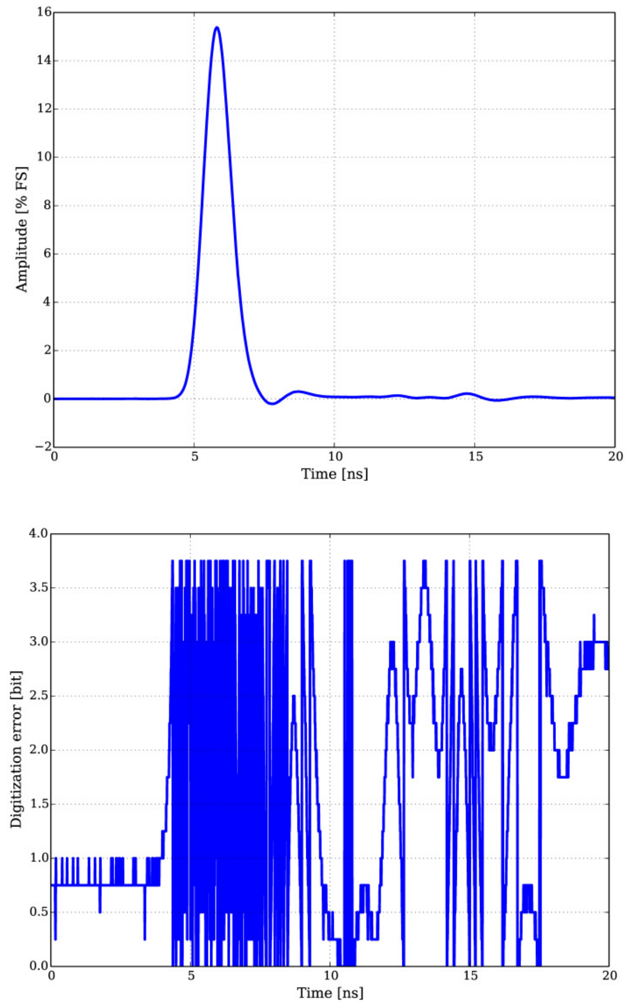

Figure 5: 8-bit dataset computed from the 12-bit dataset for the 1.2 ns pulse (top). Bits of error per sample of the 8-bit dataset obtained by comparing it to the 12-bit data (bottom).

of the increasing difference. However, for the remaining wider pulses this is no longer the case and the difference becomes smaller as the pulse stretches. The measurements show that the 8-bit resolution of the integrated signals causes an error in the order of 4 % and this is the quantified advantage of the 12-bit oscilloscope.

The source of such a large difference between the 12-bit and 8-bit integrals is demonstrated in Fig. 5 on the example of the 1.2 ns pulse, shown in the top plot for the time range taken for the integral calculation. The bottom plot shows the difference between the original 12-bit and its 8-bit version. The largest difference is close to 4-bits and its changes are related to the rate of change of the analysed pulse. The difference is the smallest during the time before the pulse for which the channel error was supressed. It is not the case for the time after the pulse, where a large difference can be seen, just changing slower than for the pulse. Therefore, the difference of the 12-bit and 8-bit integrals depends on the choice of the

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integration interval. The used 20 ns integration window was chosen as the value close to the one used by the analogue integrators of the LHC intensity monitors as well as their digital successors under development.

Table 2 summarises the results concerning the influence of the sampling rate and the integration method. All the integrals were calculated upon the longest 3.4 ns pulse with the rectangle and trapezoidal methods and, as in the previous measurements, on both the original 12-bit and the "artificial" 8-bit records acquired with six different sampling rates. All lower sampling rates were produced by decimating the only "truly measured" 125 GS/s record. The 12-bit trapezoidal integral of this original record was taken as the reference for all error computations.

As seen in the table, there is no significant difference between the trapezoidal and rectangle integrals for neither the 12-bit nor the 8-bit data for all the studied sampling rates. The sampling rate can be reduced by some two orders of magnitude before the integration error exceeds 0.1 %. This leads to the conclusion that once the sampling rate is sufficient for a given signal length, further increasing the sampling rate does not improve significantly the integrals. On the other hand, the additional four bits of vertical resolution improved the accuracy of the integrals for each sampling rate by more than 2.5 %.

CONCLUSIONS

The recent availability of fast 12-bit oscilloscopes opens a new era in laboratory measurements, for which the higher signal resolution plays an important role. It was certainly the case for the laboratory evaluation of the LHC intensity monitors, whose output signals have to be integrated with high resolution to quantify their performance [1].

As presented in the paper, the 12-bit oscilloscopes offer a much better accuracy of charge measurement than the standard 8-bit instruments, limited to a few percent for the cases studied in the paper. It was found that the post-processing integration of 12-bit signal records can be by far more accurate than the results obtained with the oscilloscope built-in integration functions, which suffer from the influence of the offset error. As demonstrated, this error can be efficiently suppressed in an adequate post-processing.

The very interesting Random Interleaved Sampling (RIS) acquisition mode, allowing achieving a very fast equivalent sampling rates, was used to study the influence of the sampling rate on the accuracy of the signal integrals. It was found that the rectangle and trapezoidal integration methods give very similar results.

All the presented integral measurements were relative and performed with the same oscilloscope channel. This way the results and the conclusions were independent of the oscilloscope gain. If absolute charge measurements are required, then the oscilloscope gain must be calibrated with a precise reference.

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