Achieve High Speed, Multichannel Data Acquisition with the Agilent M9703A AXIe Digitizer

Application Note

Challenge the Boundaries of Test
Agilent Modular Products

Achieve channel to channel coherency while accelerating test throughput for radar, satellite beam forming, MIMO and high energy applications.

Abstract

In many multichannel high speed data acquisition applications, such as radar, satellite (beam-forming), MIMO, or high-energy experiments, it is critical to have phase-coherent channels for accurate data acquisition whether for demodulation, antenna calibration, channel sounding, or event capture. Large-scale experiments may require the use of tens or hundreds of synchronized channels, and very precise time correlation between channels. Therefore, synchronization across multiple instruments is primordial.

This application note describes the measurement and analysis of cross channel skew in multichannel high speed digitizers over short and long durations to sub-picosecond scales. Two measurement techniques using the Agilent M9703A High Speed Digitizer are described and compared, and the results presented.

Figure 1. M9703A AXIe 12-bit digitizer.

Figure 2. M9703A AXIe 12-bit digitizer and M9536A embedded AXIe controller in M9505A 5-slot chassis.

Anticipate ___Accelerate ___Achieve

Agilent Technologies

Introduction

High speed digitizer systems operating at well above 100 MS/s are being used in a diverse range of applications from single-pulse linear induction accelerators to amplitude and phase measurements on multiple antenna radars. A growing number of such applications require simultaneous measurement of high frequency signals over many channels. In some of these applications, high speed data acquisition is used to capture events in the time domain, where the time parameter is often used as a measure of other parameters such as energy or distance. In frequency domain measurements, phase parameters of various signals can be of utmost importance.

Most high speed digitizers or oscilloscopes feature a maximum of only a handful of channels. For applications requiring tens or hundreds of channels and very precise time correlation between channels or accurate phase of continuous signals, it is necessary to synchronize the sampling clocks of multiple instruments.

Agilent developed a solution using front panel dongles for the interconnection of clock ASIC components for transfer of high speed ADC clocks and trigger lines across neighboring modules in a CompactPCI chassis. Using this method, up to seven modules could be synchronized and calibrated to create a 28-channel instrument. This has been used in multiple experimentation arrangements including plasma physics[1] and nuclear transmutation[2].

It is possible to achieve synchronous sampling across a great number of acquisition channels, and measure the sub-nanosecond time delays between the samples of different channels[3]. Synchronous sampling means any two channels A and B acquiring data in synchronous sampling mode, where the i^{th} voltage sample u_{Ai} is the measured signal voltage on channel A at time t_i, there is a corresponding sample u_{Bj} measured on channel B at time $t_j = t_i + \Delta_{AB}$. Here Δ_{AB} is the delay between the channels, which is the combination of the sample clock delay plus the difference in analog path lengths of B with respect to A. Synchronous sampling is maintained when Δ_{AB} is constant over all i values. By comparison of reconstructed single frequency waveforms from acquisitions on channels A and B, we can eliminate the sampling clock delay such that Δ_{AB} represents only the difference in analog path lengths, or the cross channel skew.

1. *Timing and data acquisition system for MAST high rate Thomson scattering, S. Shibaev, et al., UKAEA FUS 520, EURATOM/UKAEA Fusion, January 2005.*
2. *The neutron capture cross sections of 237Np(n,γ) and 240Pu(n,γ) and its relevance in the transmutation of nuclear waste, C. Guerrero, et al., proc. International Conference on Nuclear Data for Science and Technology 2007, p627-630.*
3. *Creating synchronous high frequency sampling across multiple digitizers, Y. Maumary, Agilent Measurement Journal 5, May 2008, p50-55.*

Depending on the end-user application, two channel delay parameters are commonly used: cross channel skew and phase delay. Cross channel skew is measured in seconds between two channels, where as the cross channel phase delay between channels is the delay in radians ($\Delta\phi_{rad}$) or degrees ($\Delta\phi_{deg}$) of the period of the input signal. One can simply be derived from the other using the relation:

$$\Delta\phi_{rad} = \Delta_{AB} * f_s * 2\pi \quad (1)$$

or

$$\Delta\phi_{deg} = \Delta_{AB} * f_s * 360 \quad (2)$$

where f_s is the frequency of the signal at the input channels in Hz.

Cross channel phase measurement methods

Various methods can be used to measure cross channel skew. The simplest method uses a fast signal pulse that is distributed to the measurement channels, and the pulse peak times can be observed in each channel. Methods that identify zero crossing points of a single tone signal can also be used. These methods do not provide the accuracy required to measure the cross channel skew in the M9703A digitizer. The digitizer comes in an AXIe form factor[4] and provides eight high speed data acquisition channels, each with 12-bit resolution, sampling at 1.6 GS/s with an analog bandwidth of 2 GHz.

Two methods were used in the cross channel skew measurements described in this document. These techniques were selected to make use of the same acquisition data – acquisition of a single frequency sine wave to arrive at a final skew measurement. This provided confirmation of the validity of both techniques, which in practice, have functional trade-offs.

Sinefit approximation

Fitting sine waves to recorded data is one of the basic test methods proposed by the IEEE standard for digitizing waveform recorders[5]. A sine wave function is adjusted in phase, amplitude, DC offset and frequency so that the square of the difference between the function and the captured single frequency sine wave data are minimized. If the identical signal is delivered to multiple channel input connectors, the samples from each waveform can be positioned to a reference instant in the signal itself. As a result, the differences in the resulting sine wave functions can be used to calculate the cross channel phase delay, and skew between channels. It is also possible to show delays between digitizing channels by repeatedly measuring the sampling instants of each relative to another.

4. *www.axiestandard.org*
5. *IEEE standard 1057, Trial-Use Standard for Digitizing Waveform Recorders, 1989.*

Accurate measurements of the cross channel skew require a precise time reference common to both instrument channels. The trigger instant constitutes the only time reference for the waveform data from the digitizer itself. Unfortunately, many factors affect the precision of this time reference. For example, the path of the input signal, and of the analog-to-digital converter (ADC) data once the signal is converted, is different from the path of the trigger signal on the digitizer board, implying different propagation delays. Components on these paths have propagation delays that vary from component to component. This is the trigger-vs.-channel delay, D_{TRIG}.

The starting point is a time reference, which is needed to accurately position the samples on an absolute time scale. Because the trigger instant is known to a precision much larger than that required for a measurement, the measured signal can be used as the absolute time reference. In this case, it must be exactly the same signal delivered to the channel inputs.

This method uses the trigger time information from the digitizers for one purpose: to determine the starting samples in each waveform. This yields a measurement of the cross channel skew that is free of the errors and jitter caused by digitizer trigger systems. The trigger comparator also can affect trigger time precision. The comparator threshold is calibrated to a finite resolution, and any noise on a signal entering the trigger comparator causes trigger time jitter.

The measured samples from each channel must be taken during the same period of the input signal. Therefore, the digitizers must be triggered at exactly the same time using an external trigger pulse. Note that this trigger pulse is completely asynchronous to the signal and the clocks. Even without using the trigger time from the digitizer, it is known that the first sample from each waveform is taken for a given trigger instant, within the period:

$$si + D_{TRIG} + J_{TRIG} \qquad (3)$$

where si is the sampling interval and J_{TRIG} is the trigger jitter.

The frequency of the input sine wave should be chosen appropriately. A higher frequency will provide better timing accuracy, but the period must be long enough compared to the period expressed in Equation 3 above, to resolve the ambiguity due to the period folding. Also, more samples per period will allow the sine fit to converge without having to specify the frequency.

Finally, the sine wave frequency should have digitized samples of different phases for each period over the complete acquisition time window. Nonlinearity errors, such as those due to the ADC, eventually translate into time errors and can be eliminated by the averaging effect of the sine fit over many periods.

The principle of using a sine fit over many periods will average out digitizer imperfections such as nonlinearity in ADCs and high frequency phase noise in the sampling clock generator. The only remaining errors come from low frequency phase noise in the clock generators. The stability of the cross channel skew can be verified by repeating the measurement over many acquisitions.

This fitting technique was relatively slow, as we first needed to acquire the triggered data across all the channels before performing the fitting and subsequent phase and skew calculations, but the process did allow us to measure the channel skew at frequencies outside of the Nyquist frequencies.

Digital Down Conversion

Nyquist theory tells us that we can reconstruct a signal exactly from its samples, provided we've sampled the signal with sufficient density. This implies that with the correct approach to reconstruction, the accuracy of a phase measurement of a tone is only limited by noise and other spurious signals that might be present; see Figure 3, below.

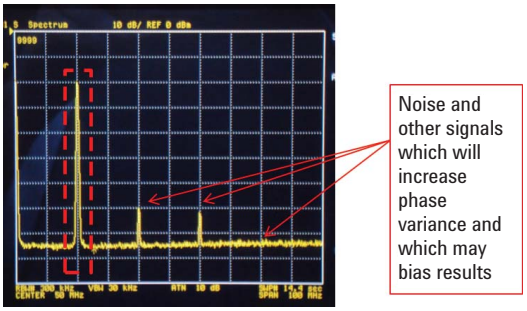

Figure 3. Noise and other spurious signals that may impede phase measurement.

Averaging can often be used to remove the effects of additive signals which are uncorrelated. However, spurious signals may still bias phase estimation results if they are correlated. Correlated signals are often the result of non-random quantization errors and nonlinearities. The digital down conversion (DDC) approach improves accuracy by removing error contributors prior to computing phase. This improves the effective number of bits (ENOB) at the expense of reduced bandwidth.

The DDC process is illustrated in a block diagram in Figure 4, on the next page. The approach first uses a digital local oscillator to center the test tone at (or near) 0 Hz. Note: there is no restriction on the test signal's frequency other than it is contained within a Nyquist interval. The frequency shifted signal, which is now complex, having both a real and imaginary part, is then low pass filtered. The filtering is symmetric about DC removing most of the noise and spurious signals, leaving untouched the test signal near DC.

Given that the signal's bandwidth has been greatly reduced, the sample rate is then reduced by decimation to a rate appropriate to the new bandwidth. This can reduce the amount of data required for a measurement to as little as a single complex sample per measurement – greatly reducing the amount of data to transfer.

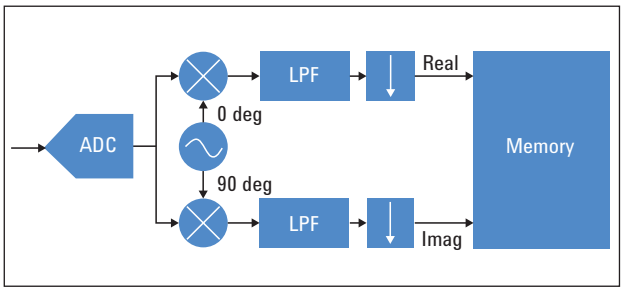

Figure 4. A block diagram of the DDC process.

When the test signal is at exactly 0 Hz, then the phase of the tone on each channel (relative to the synchronized LO's) can then be estimated directly from individual sample as *atan2(Im,Re)*. However, this is not the optimal approach.

The goal is to measure cross channel phase variation. This is best done by computing the conjugate product of the signals from two channels and then integrating over time. With this approach, the signal does not need to exactly be at DC. This approach also helps mitigate the effects of short term instability (e.g. phase noise) in the test signal or digitizer, provided the modulation is within the LPF bandwidth. When the two signals are conjugate multiplied, any phase modulation common to both channels is cancelled. As an added benefit, as the number of samples increases (longer integration time), thermal noise contributions to cross channel variance will be further reduced as these noise sources are uncorrelated and the expected value of their conjugate product is zero.

Let *r(t)* be the reference channel at the DDC output, and x(t) be a signal from another channel. Let $X = [x0\ x1\ x2 \ldots xn\text{-}1\ ]$ be N complex samples of $x(t)$, Let $R = [r0\ \ r1\ \ r2 \ldots rn\text{-}1\ ]$ be N complex samples of $r(t)$.

The complex number *G1* that represents the cross channel response is:

$$G1 = \frac{\sum_{n=0}^{N-1} x(nT) * r(nT)^*}{\sum_{n=0}^{N-1} r(nT) * r(nT)^*} \quad (4)$$

or

$$G1 = \frac{XR'}{RR'} \quad (5)$$

where R' is the conjugate transpose of R. The cross channel phase is then:

$$\Delta\phi_{rad} = atan2(Im\{G1\},Re\{G1\}) \quad (6)$$

Hardware configuration

The hardware arrangement for these experiments used a number of elements. The single tone sinewave was generated using an Agilent N5182A vector signal generator (VSG), though it is also possible to use the Agilent M9381A PXIe VSG. This signal was passed through a tunable Lorch microwave bandpass filter to remove any residual harmonics from the generated waveform. The signal was then split into eight equal signals, using three power dividers, one divide-by-two, followed by two identical divide-by-four. The output of the divide-by-four power dividers were connected to the input channels of the digitizer(s) by semi-rigid 8 cm cables.

The digitizer chosen for these measurements was an Agilent M9703A. This 12-bit digitizer has eight input channels, each sampling at 1.6 GS/s (gigasamples per second), and with an analog bandwidth of 2 GHz. The channels of this unit can be interleaved to double the available sample rate to 3.2 GS/s, but this functionality was not used in these measurements. The M9703A is in the AXIe (AdvancedTCA eXtension for Instrumentation) format, which provides an eight lane high speed PCIe interface to a controlling processor. The digitizer was placed in an AXIe chassis, and controlled over an eight lane PCIe cabled interface by a desktop PC (Dell T5500). Two system synchronization and triggering schemes were used in these measurements.

The firmware of the M9703A used, provided individual treatment of the data processing unit (DPU) timing such that each pair of channels can be considered as a synchronized 2-channel digitizer. Clock and trigger time stamping of the data from channels 1&2, 3&4, 5&6, and 7&8 are treated individually, and the positioning of the first sample in each acquisition with respect to the trigger signal is read and used to align the data acquired to the trigger. The latest version of the firmware now uses these parameters within the self calibration routine to align the sampling clocks across the digitizer channels.

Figure 5, on the next page, shows the basic set up used for the measurement of cross channel skew within one M9703A digitizer. The test signal was fed to all eight channels of the unit, with the 10 MHz reference from the signal generator used to provide the reference for the 100 MHz AXIe backplane reference. The acquisition was then triggered by an asynchronous 1 kHz signal from a 33220A function generator, the signal cabled to the external trigger input of the digitizer module.

To measure the long term stability of the cross channel skew, a third arrangement as shown in Figure 6, at right, was used. Here rather than an external reference, an external ADC clock source was provided from an E4428C analog signal generator. This external ADC clock signal replaced that generated by the on board PLL, and was distributed internally by the clock distribution circuits of the module. In order to maintain constant temperature measurements the entire experimental setup was installed in a temperature controlled environment, maintained at 25°C.

Cross channel skew measurement results

As in any system the total skew, or phase delay between channels is dependent not only on the digitizer but on the entire system path delays leading up to the channel inputs. Similarly the self calibration routine of the digitizer used in these measurements corrects for the minute path delays on each initialization, it was not practical to measure absolute cross channel skew, but rather the stability of the skew over time, after a single calibration of the instrument.

To show the stability of the synchronization we calculated the variance over multiple acquisitions, showing the distribution of the cross channel skew measurements within a measurement set.

Cross channel skew variance as a function of input power

Measurements were made with input frequencies of 100 MHz and 300 MHz. Tables 1 and 2 on the next page show the variance values for both methods at 100 MHz and 300 MHz respectively. Figures 7 and 8 on the next page show these results graphically with data points from the sinefit method connected by a solid line and the results obtained from the DDC method connected with a dotted line. The results are presented for the skew between channels 1 and 3 (Ch1Ch3), channels 2 and 7 (Ch2Ch7) and channels 5 and 6 (Ch5Ch6). All measurements were made at 1.6 GS/s, with the acquisition of 2097152 samples lasting 1.3 ms. Input frequencies of 100. 02212524 MHz, and 300.01907349 MHz, where chosen to provide a prime number of input signal periods in each acquisition. There is a close correlation between the methods used with a slightly lower distribution at 100 MHz shown using the DDC method for input powers over -33.5 dBm. We observe consistent results with the measurements made with an input signal at 300 MHz, with variance diminishing as a function of input power. This is due to the increase in the number of ADC codes that are used as the full scale range of the digitizer is filled. To note: into the 1 V fullscale 50 ohm input channel of the digitizer used, a signal power of 6.5 dBm represents approximately 0.47 V_{rms}, and -53.5 dBm is approximately 0.7 mV_{rms}.

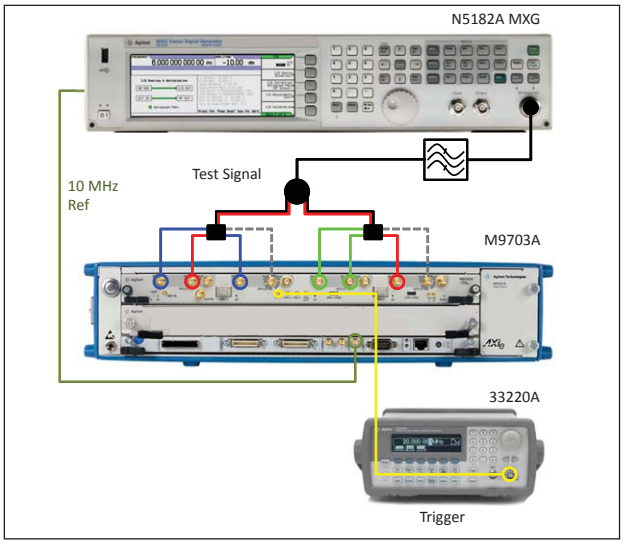

Figure 5. Hardware arrangement for single module measurements, controlling PC not shown.

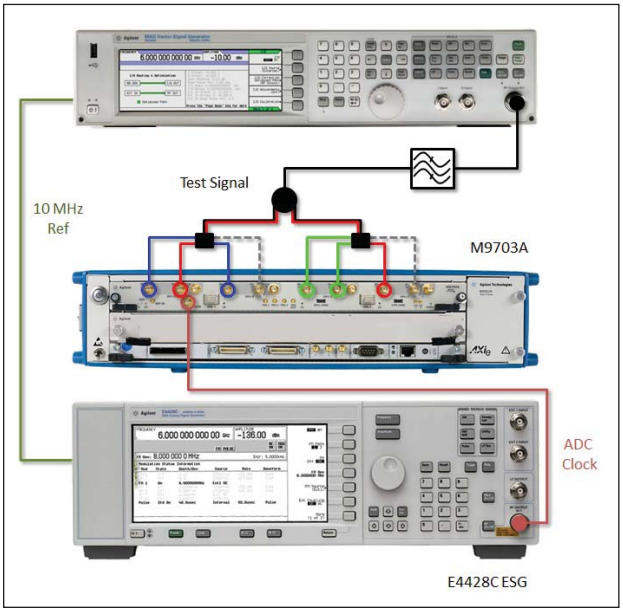

Figure 6. Hardware setup for long term stability measurements, controlling PC not shown.

Table 1. Skew variance as a function of the input 100 MHz signal power over ten measurements.

	SineFit Method			DDC Method		
	Skew Variance (sec^2)			Skew Variance (sec^2)		
Input Power (dBm)	Ch1Ch3	Ch2Ch7	Ch5Ch6	Ch1Ch3	Ch2Ch7	Ch5Ch6
6.5	4.81E-26	2.02E-24	2.10E-27	5.49E-26	1.97E-24	1.30E-27
-3.5	1.17E-27	9.54E-26	3.25E-26	7.07E-28	9.90E-26	2.53E-26
-13.5	4.15E-27	1.26E-25	3.31E-26	5.81E-27	8.64E-26	1.75E-24
-23.5	1.61E-26	1.09E-25	6.65E-26	7.21E-26	7.23E-26	5.51E-26
-33.5	3.41E-26	1.16E-25	1.07E-25	2.74E-24	6.38E-25	1.42E-24
-43.5	1.79E-25	1.05E-24	1.93E-24	2.67E-24	6.38E-25	6.46E-24
-53.5	1.30E-23	6.16E-24	6.80E-25	4.44E-23	5.43E-23	4.65E-23

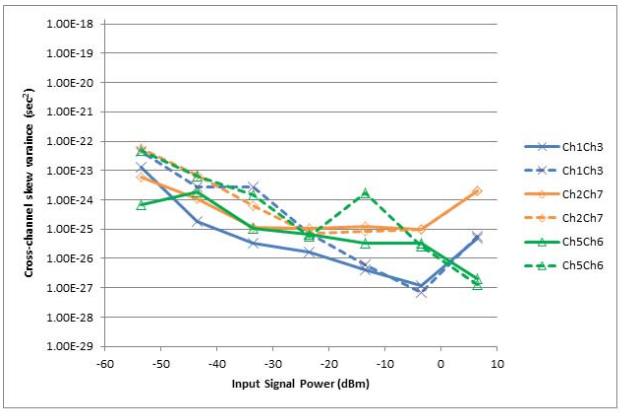

Figure 7. Skew variance plotted as a function of input signal power at 100 MHz. The solid line is the SineFit. The dotted line is the DDC.

Table 2. Skew variance as a function of the input 300 MHz signal power over ten measurements.

	SineFit Method			DDC Method		
	Skew Variance (sec^2)			Skew Variance (sec^2)		
Input Power (dBm)	Ch1Ch3	Ch2Ch7	Ch5Ch6	Ch1Ch3	Ch2Ch7	Ch5Ch6
6.5	1.27E-26	2.26E-27	3.68E-29	7.07E-28	2.48E-27	1.47E-29
-3.5	8.65E-28	2.15E-27	3.47E-29	2.04E-27	4.13E-27	9.56E-29
-13.5	5.99E-27	9.66E-27	2.82E-28	5.68E-27	1.03E-26	4.07E-28
-23.5	3.13E-27	6.45E-27	1.03E-27	1.21E-26	9.14E-27	5.06E-27
-33.5	1.09E-26	1.68E-26	2.41E-26	1.36E-25	1.11E-25	3.44E-26
-43.5	2.69E-25	4.21E-25	5.84E-25	6.92E-25	1.81E-25	1.37E-25
-53.5	4.39E-24	4.48E-23	1.13E-23	7.11E-24	5.11E-23	2.76E-23

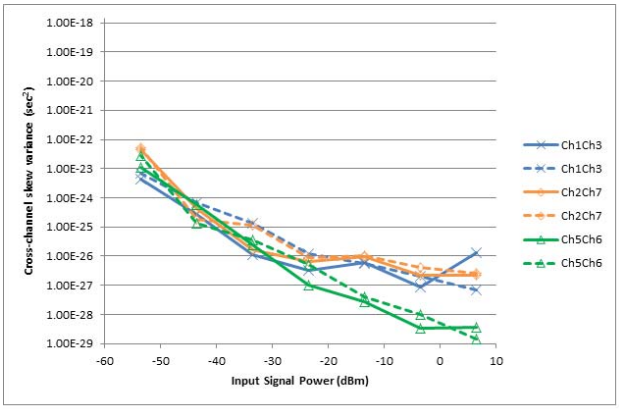

Figure 8. Skew variance plotted as a function of input signal power at 300 MHz. The solid line is the SineFit. The dotted line is the DDC.

Long term stability of cross channel skew in a controlled environment

The long term stability of the cross channel skew was measured over 17 hours, using the sinefit method with 204 acquisitions each 5 minutes apart with an input power of 6.5 dBm. Figure 9 shows the difference of the individual skew values from the average (fixed) skew, it can be seen that even with the system enclosed in a temperature controlled environment that a warming up period is needed before completely stable operation. The separation of each measurement by 5 minutes elongates this period. The largest variations are seen during this warm up period, with over 100 fs difference between channels 2 and 7. Table 3 shows the variance from the entire data set.

We see that the ADC channels that share the same ADC clock, and are supplied the input signal from the same splitter provide the lowest variance levels, the furthest pair of channels 2 and 7 showing a variance that is 30 times greater.

Conclusions and future work

This paper has shown the incredible performance available today for synchronous multichannel acquisition. Accurate cross channel timing measurements depend on more than just the digitizer performance. These measurements were made with careful choice made for the cabling, because at a system level the skew will depend not only on the path lengths carrying the input signal within the digitizer component, but also the path lengths before the digitizer. Recent popular discussion around the false measurement of neutrino speeds between CERN and the OPERA experiment at Gran Sasso, Italy have displayed the fragility of timing measurements for even the most experienced scientist, with one likely issue for the errors stemming from the loose connection of an optical fiber[1].

The architecture of the hardware used in these measurements lends itself to the use of the backplane synchronization signals, as provided by the AXIe architecture. We intend to continue this work to measure the cross channel skew in a digitizer system using multiple digitizer modules.

Table 3. Skew variance for a 300 MHz input signal for 204 measurements taken over 17 hours.

Input Power (dBm)	SineFit Method		
	Skew Variance (sec^2)		
	Ch1Ch3	Ch2Ch7	Ch5Ch6
6.5	4.81E-26	2.02E-24	2.10E-27

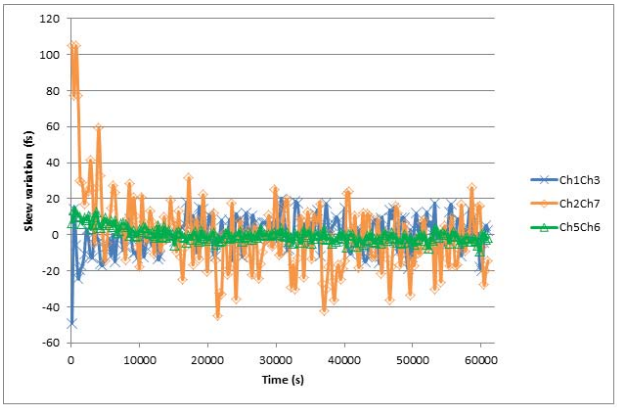

Figure 9. Skew variation from the average level, as a function of time.

1. *http://operaweb.lngs.infn.it/spip.php?rubrique14*

Ordering Information

Model	Description
M9703A	AXIe 12-bit digitizer
Base Configuration Options	
M9703A-SR1 [1]	1 GS/s sampling rate
M9703A-SR2	1.6 GS/s sampling rate
M9703A-INT	Interleaved channel sampling
M9703A-F05 [1]	650 MHz maximum analog bandwidth
M9703A-F10	1 GHz bandwidth additional path
M9703A-M10[1]	1 GB (64 MS/ch) acquisition memory
M9703A-M20	2 GB (128 MS/ch) acquisition memory
M9703A-M40	4 GB (256 MS/ch) acquisition memory
M9703A-DDC	Digital downconversion firmware

Related Products	
M9502A	2-slot AXIe Chassis
M9505A	5-slot AXIe Chassis
M9536A	Embedded AXIe Controller
M8190A	AXIe 12 GSa/s Arbitrary Waveform Generator
N5182A	MXG RF Vector Signal Generator
M9381A	PXIe Vector Signal Generator
E4428C	ESG Analog Signal Generator
33220A	Function/Arbitrary Waveform Generator, 20 MHz

1. These options are included in the default configuration of the M9703A.

Software Information

Chassis Slot Compatibility: AXIe, ATCA	
Supported operating systems	Microsoft Windows ® XP (32-bit) Microsoft Windows ® 7 (32/64-bit) Microsoft Windows ® Vista (32/64-bit) Linux
Agilent IO Libraries	Includes: VISA Libraries, Agilent Connection Expert, IO Monitor

Typical System Configuration	
M9703A	AXIe 12-bit digitizer
M9505A	5-slot AXIe chassis
M9536A	Embedded AXIe Controller

www.agilent.com/find/modular
www.agilent.com/find/digitizers
www.agilent.com/find/m9703a

Challenge the Boundaries of Test
Agilent Modular Products

To contact an Agilent representative:
www.agilent.com/find/contactus

myAgilent
www.agilent.com/find/myagilent
A personalized view into the information most relevant to you.

www.axiestandard.org

Agilent Advantage Services **www.agilent.com/find/advantageservices**

Agilent Solutions Partners
www.agilent.com/find/solutionspartners

DEKRA Certified ISO 9001:2008 **www.agilent.com/quality**

Printed in USA, February 11, 2013
5991-1941EN

Agilent Technologies