Options for High Dynamic Range Recording of Electrical Transients

ICF Diagnostics Workshop, LANL

Alastair Moore, Bart Beeman, Arthur Carpenter,
Andrew MacPhee, Gary Grim, Ed Hartouni

October 7, 2015

LLNL-PRES-XXXXXX
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

Which NIF Diagnostics need High DR?

- Dante – Hohlraum Tr
  - Benefits from high dynamic range to measure picket/trough at the same time as the peak (i.e. small signal before large signal)
  - Could also mitigate need for needing to change attenuation from shot-to-shot

- nToF – Neutron Yield, Apparent Tion, DSR (+ Neutron Spectrum Moments)
  - Needs to accurately measure rising and falling part of DT and DD neutron spectrum over 2-3 decades to establish skew and kurtosis
  - Down-scattered spectrum after initial 14.1MeV peak (so small signal after large signal)

- SPBT – X-ray burn width
  - Measurement of X-ray burn width on falling edge of large hohlraum signal (small signal after large)

A range of NIF diagnostics need High DR

What systems are currently deployed:

- Dante
  - Analog Oscilloscopes – 10-bit (ENOB ~ 7.5); 5-7 GHz (depending on cal.)
  - 20 x SCD5000 – Dante 143-274
  - 18 x FTD10000 – Dante 64-350
- nToF (SPEC, SPECA, SPECE)
  - Digital Phosphor Oscilloscopes – 8 bit (ENOB ~ 5); 1 GHz
  - Stitch 4 channels (ENOB ~ 7)
  - 4 x Tektronix DPO 7104 per nToF (12)
- SPBT
  - Analog Oscilloscopes – 10-bit (ENOB ~ 7.5) ; 7 GHz (depending on cal.)
  - 4 x FTD10000
- GRH
  - Mach-Zehnder
  - 4 x Tektronix DPO 71254 – 8-bit; 12.5 GHz

What are the typical signals and requirements?

	Dante	nToF	SPBT	GRH
Signal duration (ns)	0.1 - 60	100's	10 - 20	1 - 5
IRF rise-time (ps)	125	125	100	80
Cable effect on rise-time (ps)	250	250	250	N/A
Typical signal rise-time (ns)	1 - 2	2 - 3	0.2	< 0.1
Bandwidth reqd (GHz)	> 2	1	~5	~10
Noise floor (mV)	< 10	< 10	5 - 10	50 - 100

Each diagnostic has unique tailored needs.

High DR Recording Options

Digital Storage Oscilloscope / Digitizer
$

Pros
- Well supported & characterized
- Low noise
- Variable sensitivity (V/div)
- Excellent timebase stability
- Long record length
- Programmable bandwidth
- Inexpensive

Cons
- Sensitive front-end

Analog Oscilloscope
$$$

Pros
- Robust to high voltage spikes
- Low noise
- Good single shot dynamic range

Cons
- Difficult to maintain good calibration - V & t
- Short record length
- Expensive

Mach-Zehnder Interferometer
$$

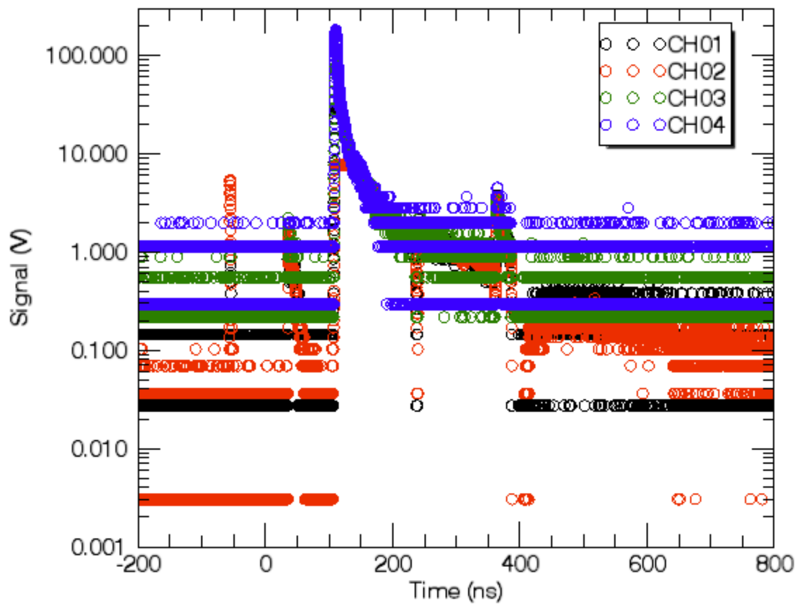
Pros
- Robust
- High bandwidth
- Suitable for hostile environ.
- Cont. record (50mV –100V)
- Excellent single shot DR
- Full sensitivity in the presence of large signals

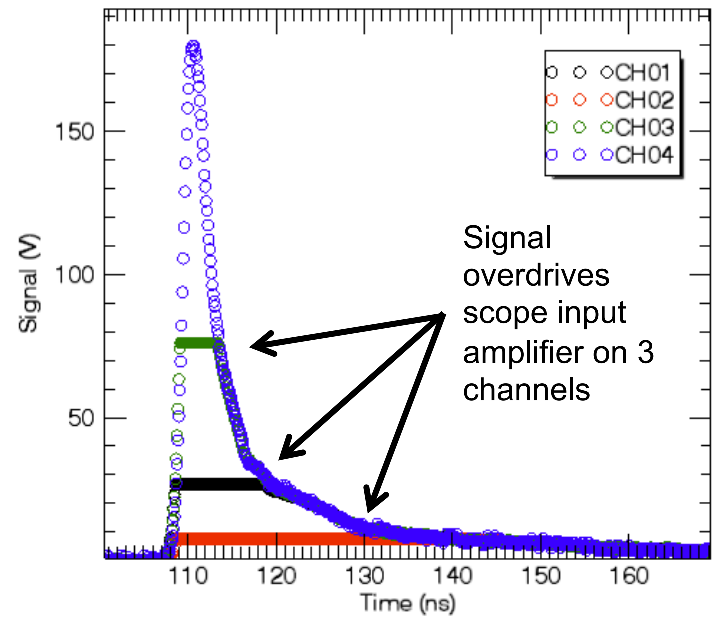
Cons
- Complex
- Raw data is not intuitive to interpret
- Moderately expensive

LLNL currently has an LDRD for a phase modulator system (similar to a MZ) – J. Chou.
Recently demonstrated >2 GHz at 7+ ENOB and think they can get to 8-9 ENOB with the next version.

Stitching is used on the nToF's to improve the dynamic range.

Split and measure the same signal multiple times with different levels of attenuation





nToF 64-330: DTHI

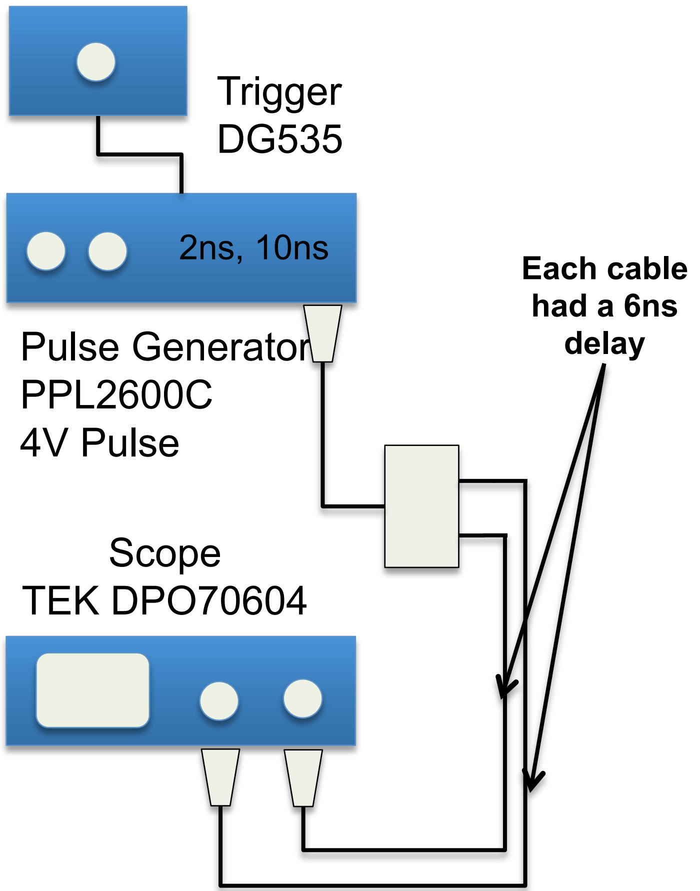
Can stitching digital signal measurements together increase DR?

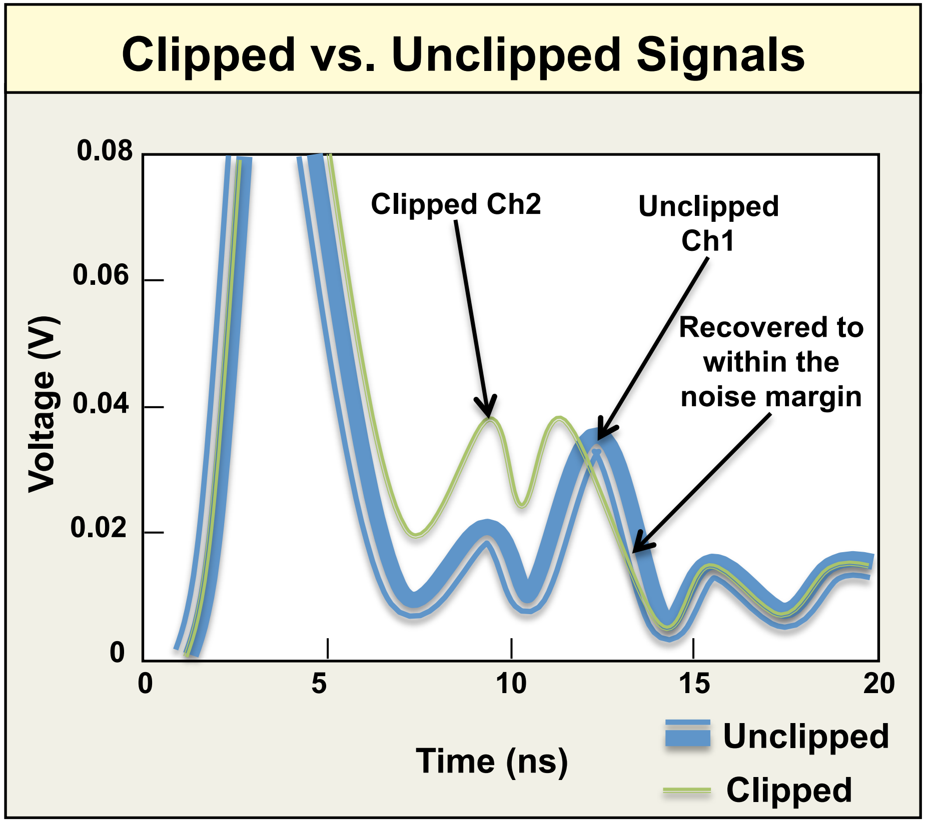
- In principal stitching multiple signals together is a robust technique, but there are details that must be accounted for.
- Most digital storage oscilloscopes when overdriven, exhibit signal distortion since the input amplifier is saturated.
- In addition digital scopes often employ some kind of finite impulse response (FIR) filter in the signal processing that corrects for the fall off in bandwidth response, which will effect samples both earlier and later in time relative to when the scope is overdriven.
- Some companies quote a recovery time (~20ns), but most just advise not to overdrive.

- This has been characterized for DPO 7104, and is a function of peak signal voltage and the degree of overdrive, plus the frequency content of the signal, so isn't completely straight forward.

Stitching may be an option, but depends on hardware used, and knowledge of the DSP

The effects of overdriving the input amplifier have been investigated

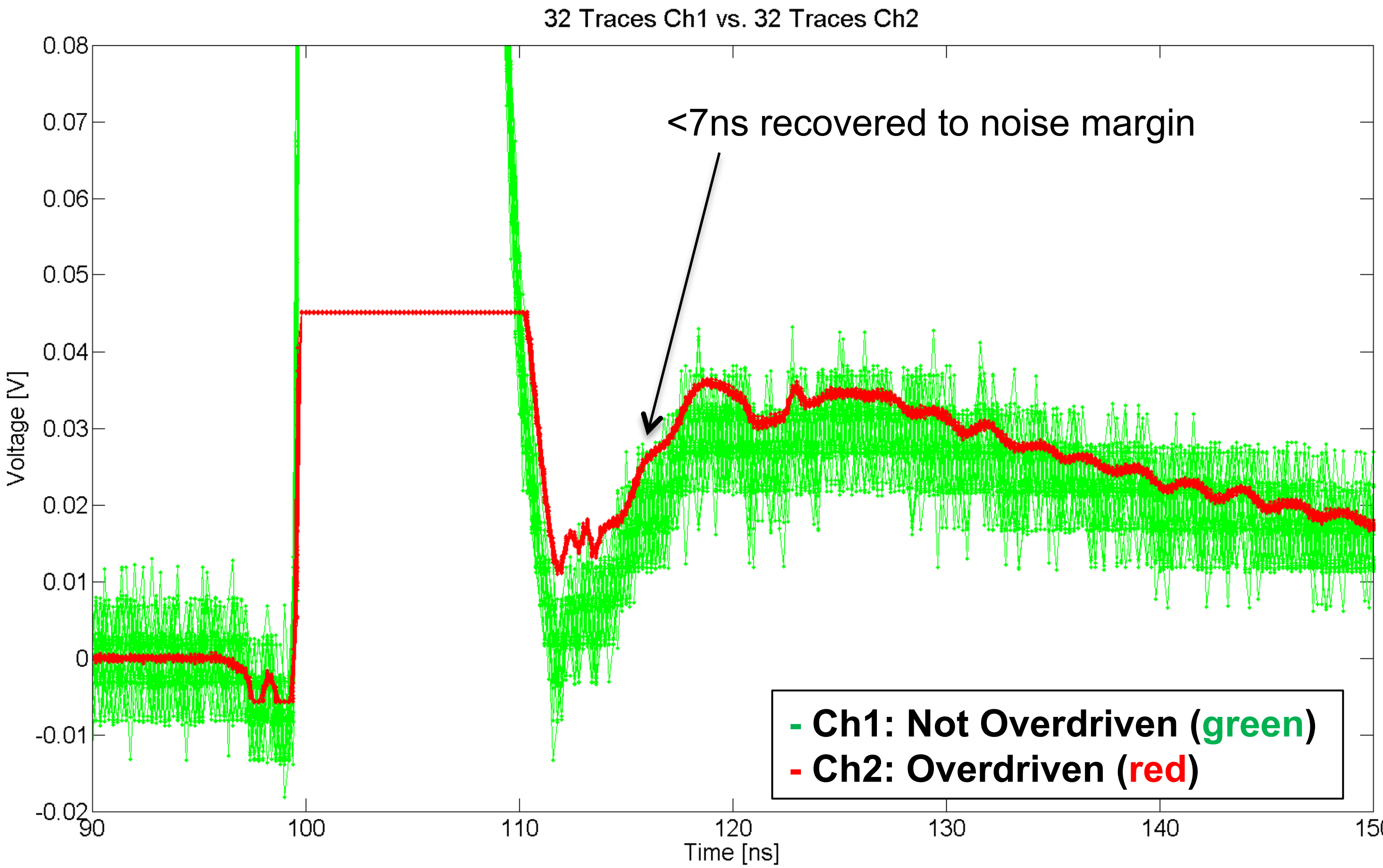




DSP: Off

A. Carpenter

Large overdrive ratio: 10ns 125mV/div and 5mV/div ~1V pulse 25x overdrive



Overdriving Results

- Recovery to noise margin generally took less than 10ns
- Worse case recovery to noise margin took 15ns
- Worse case recovery to signal average 60ns
- Large input voltages (>2.5V) cause major reflections when the preamp is active (< 100mV/div)
- Reflection amplitude is dependent on signal voltage not overdriven voltage scale
- Longer pulses (>2ns) take longer to recover to noise margin (10-15ns)
- Overdrive ratios of up to 25x with 10ns recovery times to noise margin can be obtained with reduced input voltages.

A. Carpenter

Overdriving input amplifier should be approached with catution

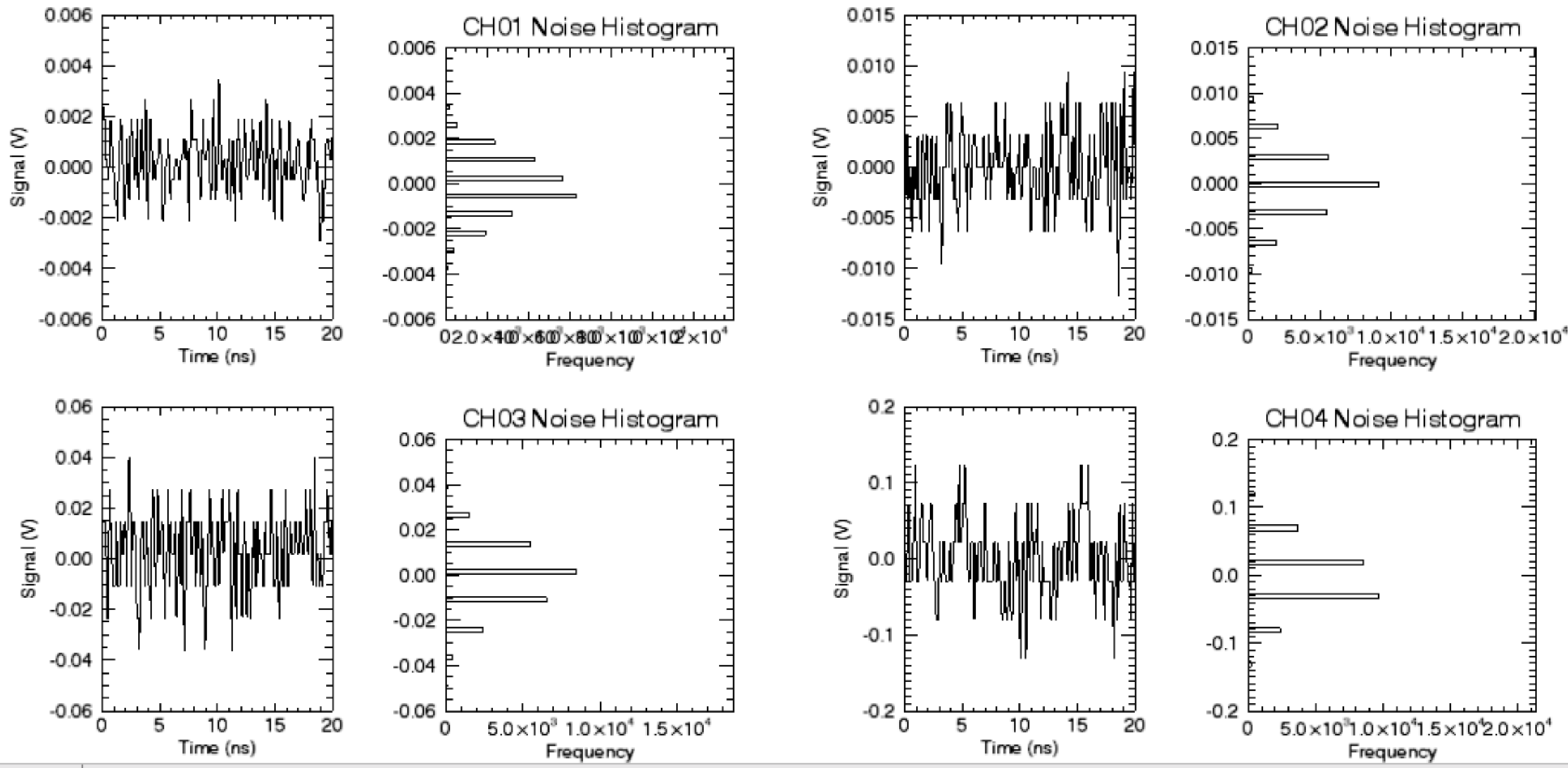
Can stitching digital signal measurements together increase DR?

Comment from John Carlin – Keysight S-Series Scope:

"Prior to being overdriven the values that come through the front end of the scope and ADC will be completely unaffected. However once we start doing response correction (either for the scope response, bandwidth limiting, or de-embedding) the scope will use a FIR filter that that is both forward and reverse looking (in real time DSP applications this is called non-causal). The number of filter taps can become quite large, 10,000 points or more depending on the application. Just for the sake of example let's say we have a 1 K filter pad to the right of any given point, if clipping happens at point N then point N – 1001 is completely unaffected, N-1000 will only have a very small error introduced, and so forth until we get to point N–1 which is in pretty bad shape."

Using DSP in Digital Oscilloscopes to improve bandwidth mean that stitching results will be compromised.

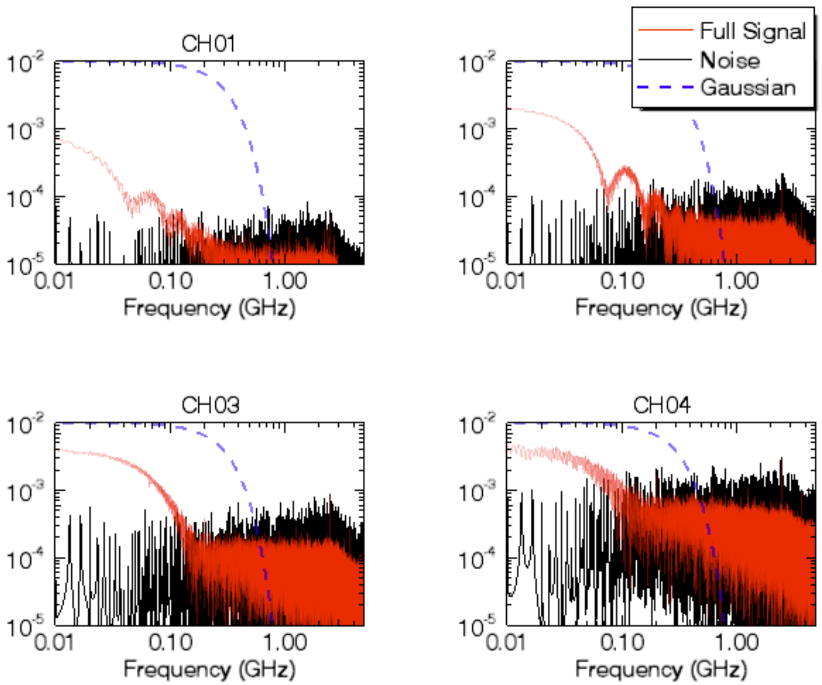
It is important to understand the operational noise floor

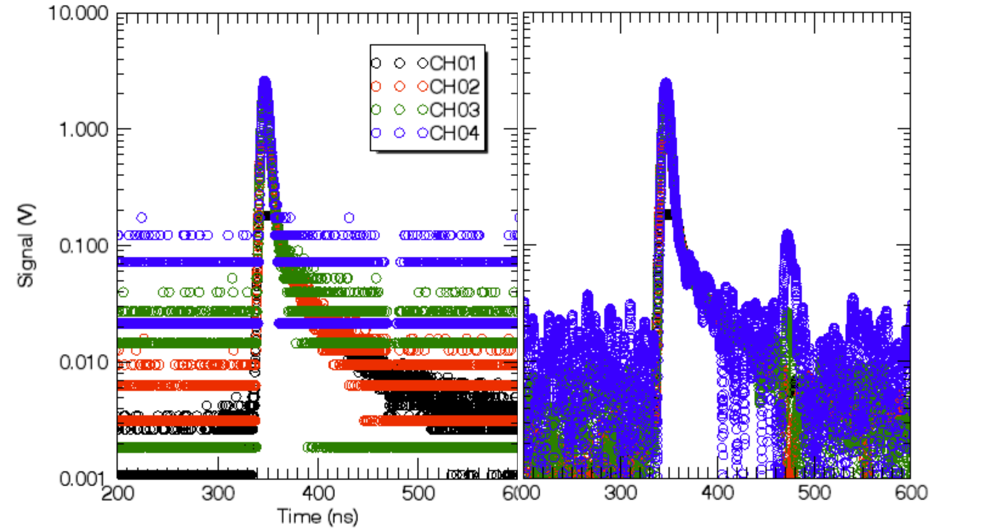


N141008 - SPECA

Typical scope noise floor is normally distributed and accounts for 5-7 ADC points

Simple DSP can help reduce bit-noise and improve ENOB: Low-pass filtering





	DR	DR (#-bit)	SNR	SNR (#-bit)
CH 01	168.6	7.4	47.6	5.6
CH 02	231.3	7.9	64.9	6.0
CH 03	170.1	7.4	57.1	5.8
CH 04	57.9	5.9	29.1	4.9
Stitched Threshold	408.8	8.7		
Stitched Low-pass			110.0	6.8

- Low Pass Filter: -3dB at 0.25 GHz
- Care must be taken over effects to rising edge and changes to peak amplitude

N141008 - SPECA

Noise floor can be effectively lowered if noise spectrum is well-understood.

Example: Dante Scope Upgrade
High Level Requirements / Key Expectations

	Key Expectation	Verification Method	Result Summary
1	Effective Bandwidth >2.5Ghz (supporting data presented below)	See test plan	Supporting data presented at CDR
2	Samples per second > = 100 ps/pt (10GS/s)	Specification	Specification
3	Cross time to NIF by better than 50ps	See test plan	FIDU split 50/50 into two chnls Mean = 9.2ps, Stdev = 3ps
4	Vnoise ~5mv single shot with 1.25v range	Measurement	5.8mV RMS with 1v pk signal shot data presented below
5	Must survive ~1kv 20ns pulses	Refer to CEA test results	25+ shots @ >225V on NIF; S-Param verification complete,
6	Stable time base	See test plan	Specification ±(12 ppb initial+75 ppb/year aging)
7	Vertical multiplexing - ANY 2 channels - Or 6 fixed channels	2 Options to be vetted	Any 6 fixed channels
8	Maximum signal voltage able to record is 150V	See test plan	Achieved with Variable Atten.
9	Will run without the need for human generated hardware changes	Except Annual Calibration (Option 1 provides possible upgrade path)	Except Annual Calibration (Automated Self test upgrade avail)
10	Direct access to the raw data	Firmware switch to disable all DSP	Raw and Scope processed data to be archived

Comparison / Trade-off Grid: Keysight S-Series Scope Selected

Dante systems engineering work_062315.xlsx - Microsoft Excel

Rank 1-10	Run without Human HW changes	Stable time base	Analog Bandwidth (>2.5Ghz)	Sample rate (10GS/sec min)	Temporal range 1-200ns at full Samp/sec	Vertical multiplexing on at least 2 (max 6) of ANY of the channels	cross time to NIF by better than 50ps	150v Maximum usable voltage (rank 8 with variable Atten)	Over Voltage Survivability (>8v - 1Kv @20ns) 6 = French clipper circuit required 5 = Fixed atten + clipper	minimum voltage able to record is 15mV (with SNR greater than 3x)	Vmin with 1.25v Scale <5mv Single shot dynamic Range (ENOB = 8)	Easily serviceable	Direct acces to Raw Data	Calibration to better than	budget	rack s	Total	Cost/XRD * Including Atten (~$ and Mux ($70
Key Expectation Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8, 3**	**8, 3**	**9, 3**	**10, 3**	**11**	**12**	**13**	**14**			
weight (1-10)	**8**	**9**	**10**	**10**	**10**	**10**	**10**	**10**	**9**	**8**	**10**	**7**	**10**	**8**	**8**	**0.2**		
Keysight scope (2.5Ghz)	8	9	8	9	10	9	10	8	6	10	**7.4**	8	**7**	10	9	5.7	1226	**$ 16,666.67**
Keysight scope (4 Ghz)	8	9	10	9	10	9	10	8	6	10	**7.2**	8	**7**	10	8	5.7	**1236**	**$ 20,722.22**
Tek scope, coax (requires vertical multiplexing all channels)	8	9	10	9	10	**5**	10	8	6	10	**5.6**	8	10	10	3	2.9	**1190**	**$ 44,000.00**
12Ghz Tek scope, MZ	10	8	11	11	10	10	10	10	10	**0**	**8.7**	5	10	5	**2**	0.2	**1164**	**$ 50,000.00**
Digtzr card, 3slot PXIe, NI (requires vertical multiplexing all channels) (no longer avail?)	8	8	9	10	10	**1**	**4**	8	6	10	**6**	8	10	9	**1**	8.3	1052	**$ 58,600.00**
Pizza box, GreenField	8		9	9	8	9	7	8	5	10	10	5	10	5	3	5	1074	**$ 28,477.78**
Digtzr card, PCIe, KeySight	8	9	10	9	10	9	10	8	6	10	**7.2**	8		10		28	**1111**	**??**
FTD10000	8	**3**	10	10	**6**	7	7	8	10	10	**11.2**	**1**	10	**3**	**1**	0.3	1087	**$ 80,700.00**

Actor Description / Stakeholder / Trade space / Trade Space (2) / **Trade Space (3)** / Recording system sp

Select destination and press ENTER or choose Paste

Conclusions

- High Dynamic Range digitization is sought-after by a wide range of HED and ICF diagnostics, since it can improve the accuracy of models and understanding of underlying physics.
- Each diagnostic has unique needs tailored to the particular signal/ environment etc.
- Stitching is one way to increase DR but overdriving input amplifier must be approached cautiously – any onboard DSP can invalidate an overdriven trace – depends on scope – some appear better than others.
- MZ systems can also increase DR, but at cost of complexity and noise floor.
- It is helpful to know the detailed requirements optimize the system design - everything is a trade-off!

Lawrence Livermore
National Laboratory