National Physical Laboratory

Pulses and Parameters in the Time and Frequency Domain

David A Humphreys
National Physical Laboratory
(david.humphreys@npl.co.uk)

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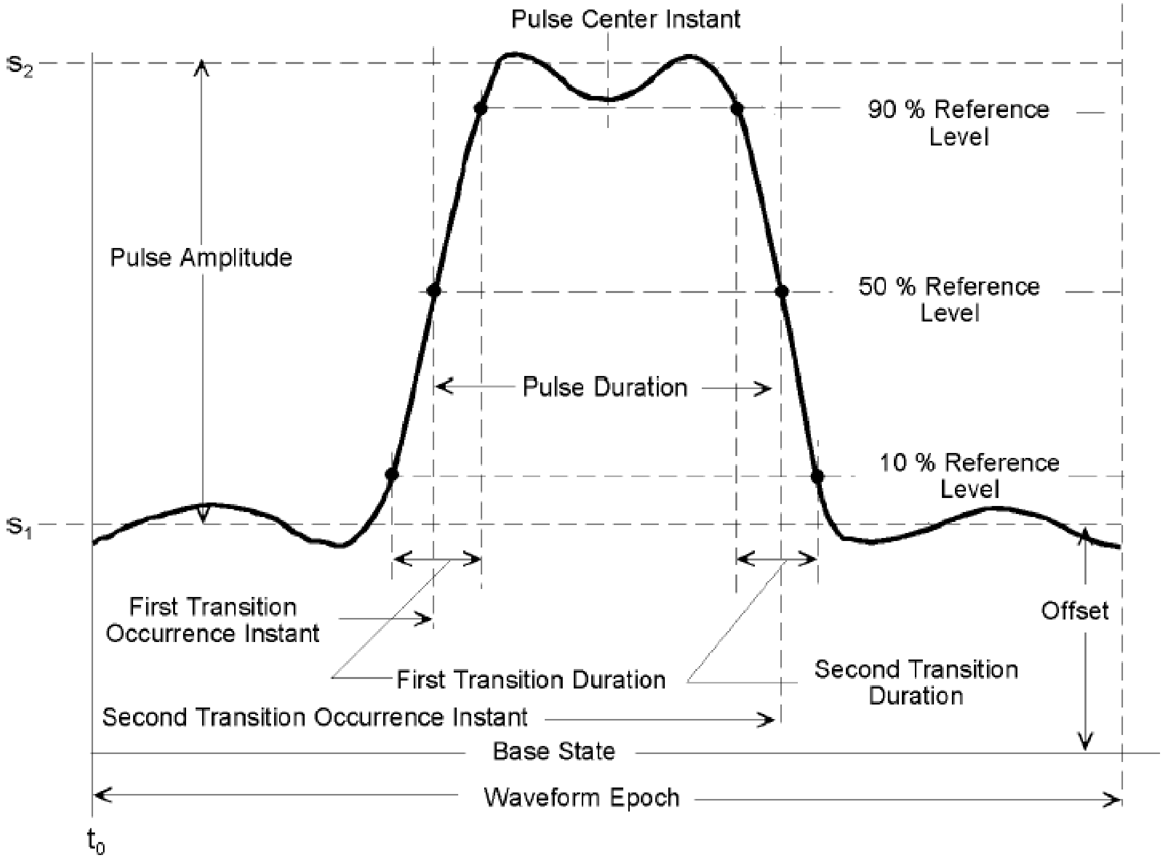
Structure

- Introduction
- Waveforms and parameters
- Instruments
- Waveform metrology and correction

Waveforms and parameters

Parameters for a pulse waveform



Why use parameters?

- Convenient way to compare information
- Reduce data complexity
- Specification of instruments
- IEEE Standard on Transitions, Pulses, and Related Waveforms, IEEE Std 181, 2003
- These documents standardise how to characterise a *waveform* but do not specify units

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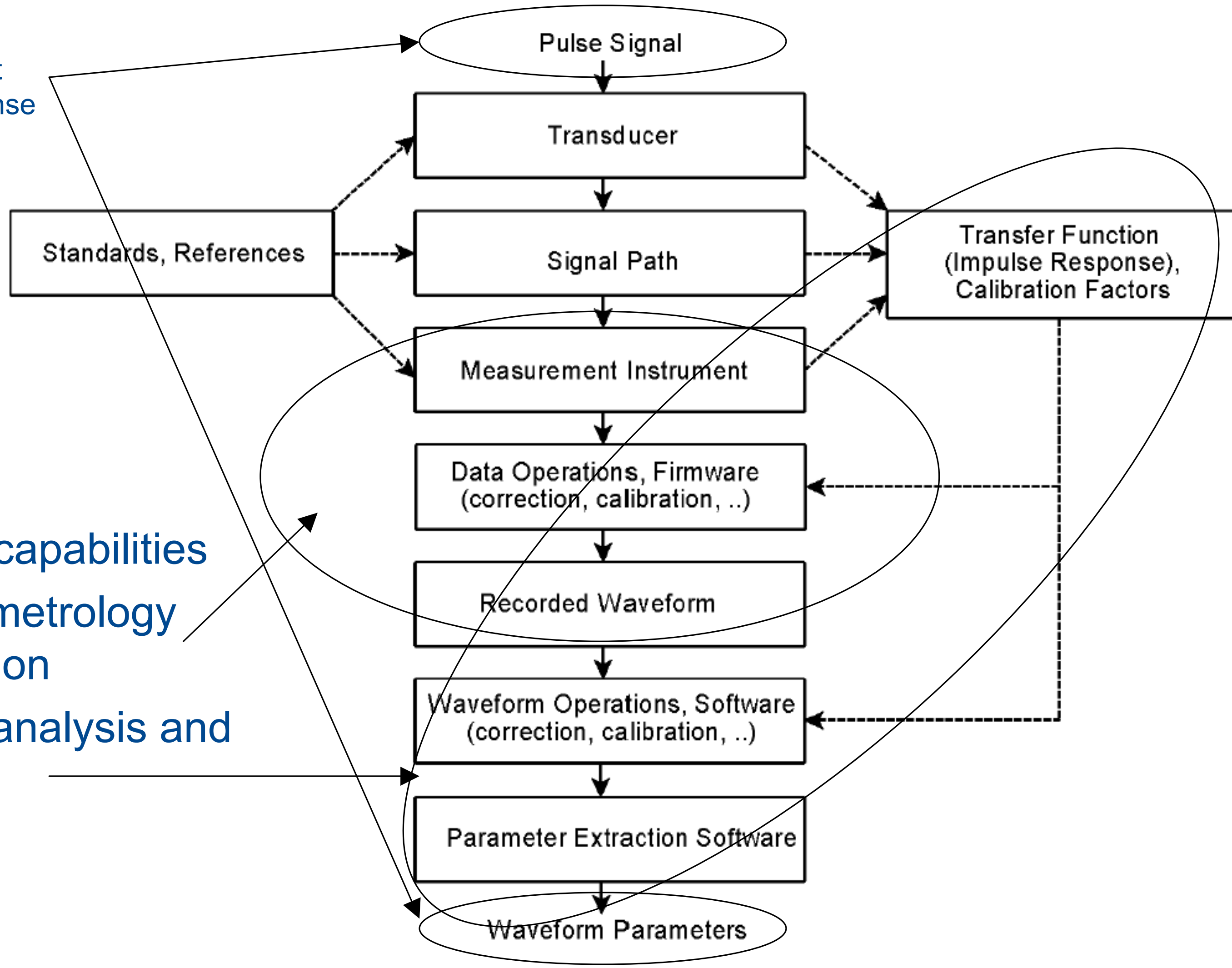
Measuring and characterising a signal

Determine parameters that describe a signal or response

I. Instrument capabilities

II. Waveform metrology and correction

III. Parameter analysis and extraction



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Assumptions

- In practice we want to define a response in terms of single parameters such as width or risetime or bandwidth

- Assume oscilloscope response has smooth bell-shaped

  e.g. Gaussian

  Simple analytically

  Can calculate frequency response, convolution simply, reasonably realistic

  Only 3 parameters – width/risetime; amplitude and position

Instruments

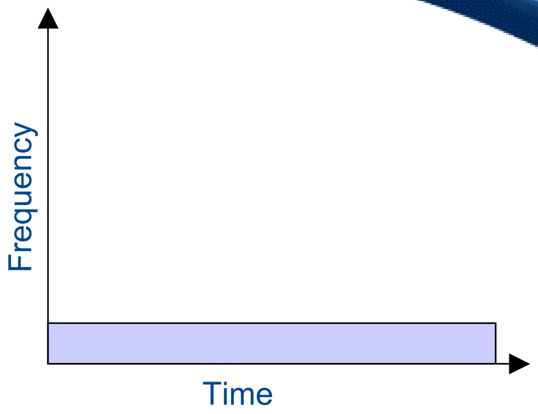
Instrumentation

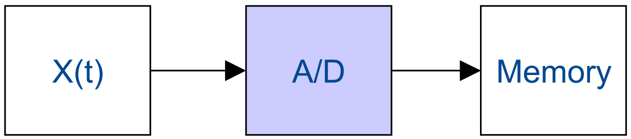
- Time-domain

  Real-time oscilloscope

  High-speed A/D converter

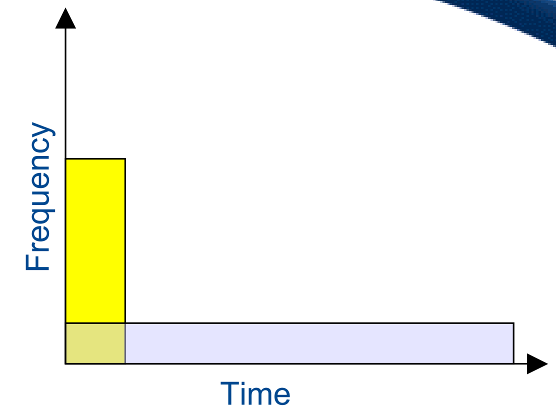
  Memory subsystem e.g. 32 Msamples

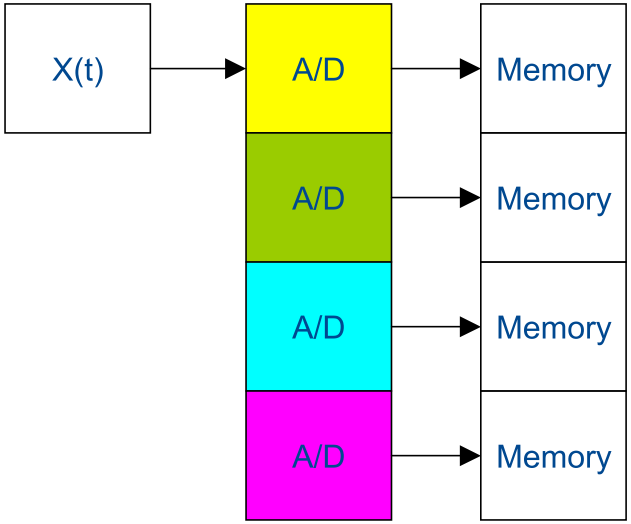




Instrumentation

- Time-domain
  - Real-time oscilloscope
    - Sample rates up to 40Gsamples/s
    - Multiple high-speed A/D converters
    - Fast memory subsystem
    - Memory architecture may limit the length of trace e.g. 1 Msamples
    - Resolution typically 8 bits





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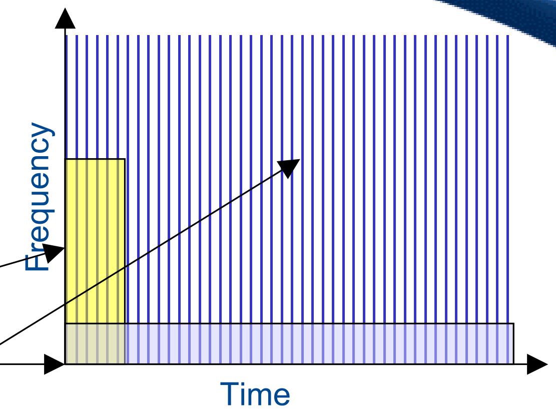
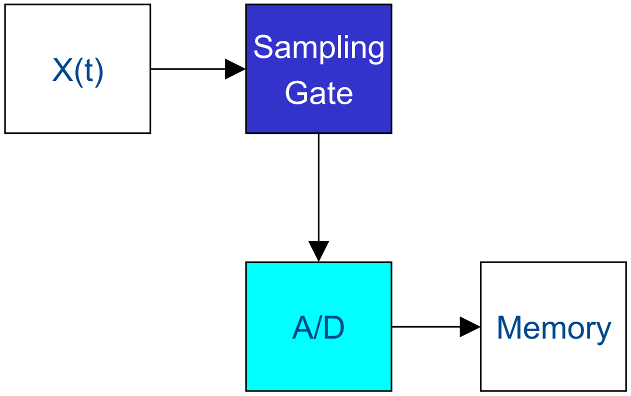
Instrumentation

- Time-domain
  - Real-time oscilloscope
  - Sampling oscilloscope
    - Requires a repetitive waveform
    - High-speed >70 GHz
    - Short trace length (e.g. 4096 samples)





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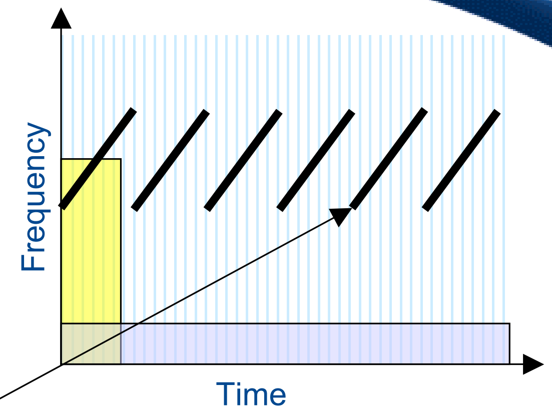
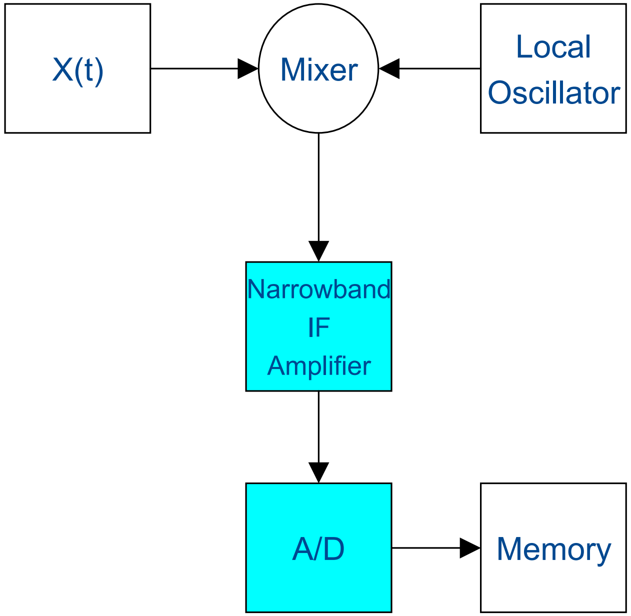
Instrumentation



- Time-domain
  - Real-time oscilloscope
  - Sampling oscilloscope
- Frequency domain
  - Heterodyne spectrum analyser
    - Narrowband IF
    - Not well suited to RF pulse measurements



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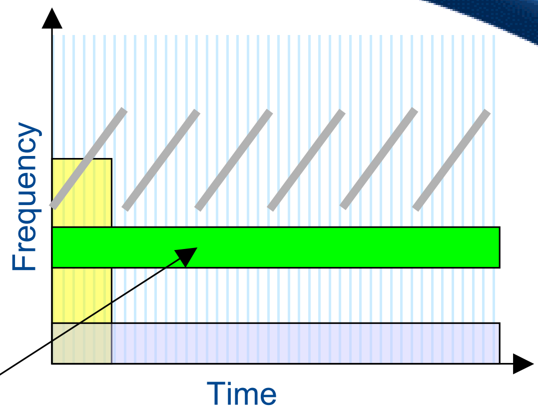
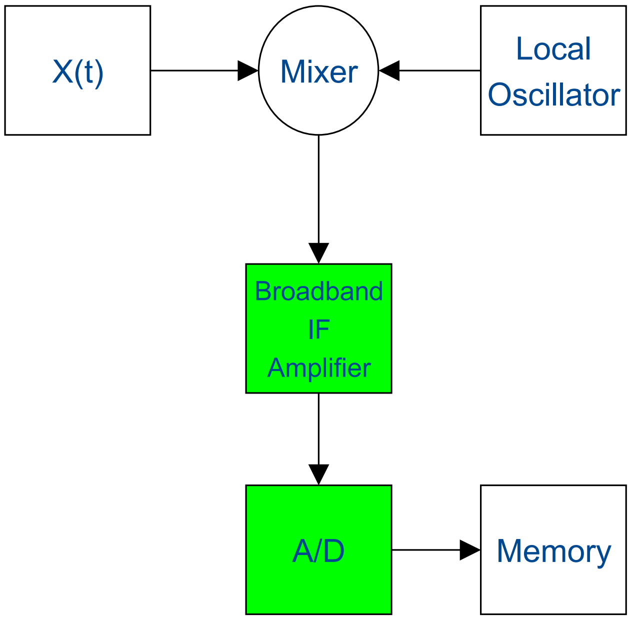
Instrumentation

- Time-domain
  - Real-time oscilloscope
  - Sampling oscilloscope
- Frequency domain
  - Heterodyne spectrum analyser
    - Wideband IF
    - Suitable for RF pulse measurements
    - Lower frequency operation (8 GHz)





Instruments to measure pulse waveform

- Digital oscilloscope – can acquire single-shot data
  Current models up to 15 GHz 40 Gsamples/s.
  Typically 8-bit resolution
- Sampling oscilloscope – requires repetitive waveform –
  Sampling rate <100 ksamp/s.
  Bandwidth up to 100 GHz.
  Typical trace lengths 1024 - 4096 points
  Typical resolution 10-bit
- Heterodyne RF Spectrum Analyser – unsuitable for this task
- Real-time Spectrum Analyser – Down-converts RF signals to low frequency
  Typical frequency range 8 GHz
  IF Bandwidth/digitiser typically 10-80 MHz

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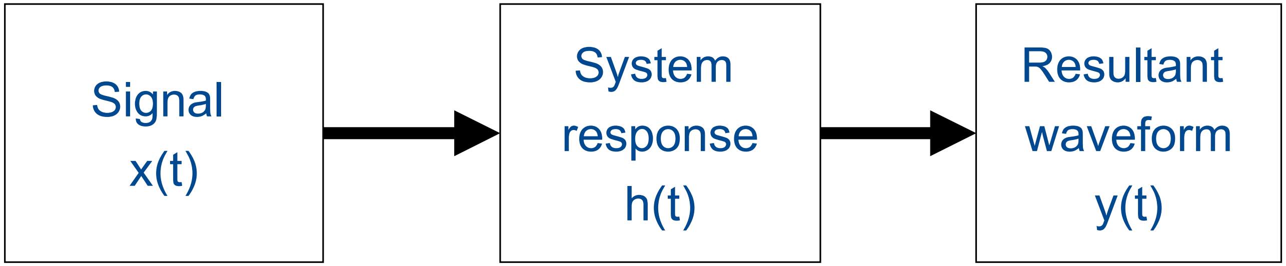
Waveform metrology and correction

Measured waveform

- Convolution of stimulus and system response



$$y(t) = \int_{-\infty}^{+t} x(\tau)h(t-\tau)d\tau$$

$$Y(s) = H(s)X(s)$$

Quadrature deconvolution

Oscilloscope automatically performs a convolution when it records a waveform.
Problem is to carry out the inverse operation and that is much more difficult.

Approximate the convolution integral to a quadrature addition.
Information required is given by quadrature subtraction.

$$TR_{CRO} = \sqrt{TR_{meas}^2 - TR_{PG}^2}$$

- **Gaussian approximation to both the pulse shapes is valid**
- **the oscilloscope response is much faster than the pulse duration.**

The rule of thumb normally adopted is that $TR_{meas} > 3\,TR_{PG}$

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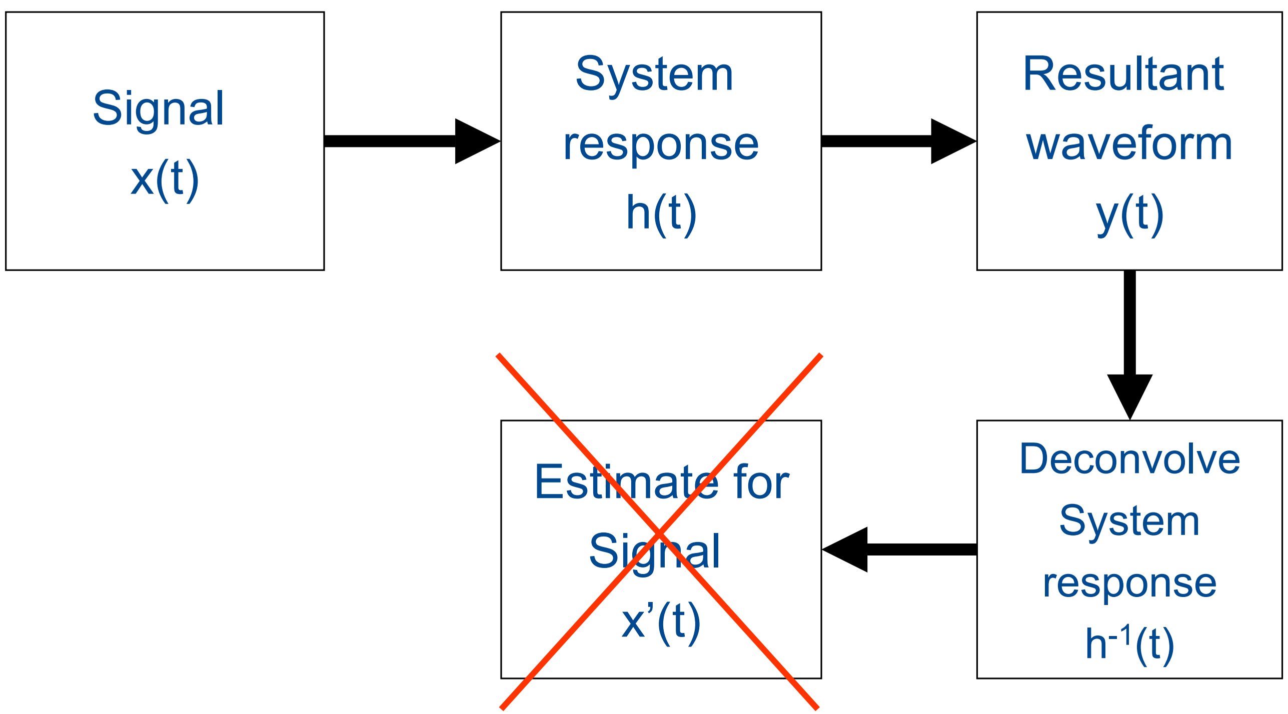
Deconvolution of measured waveform

- Convolution of stimulus and system response
- Deconvolution – correction for the system response



$h^{-1}(t)$ is the inverse of the system response h(t)

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Deconvolution of measured waveform

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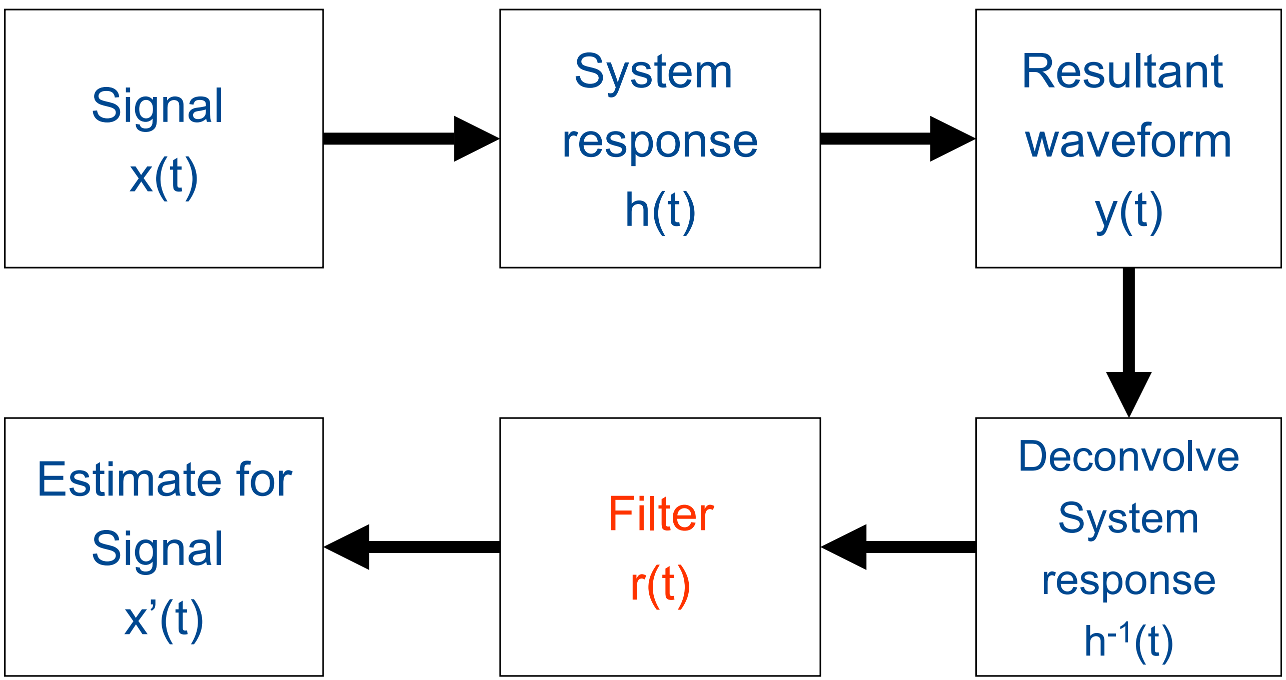
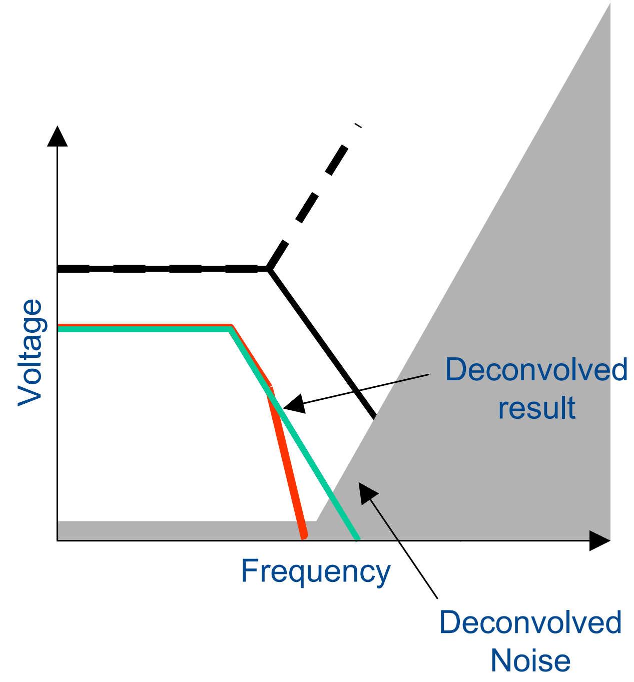


$h^{-1}(t)$ is the inverse of the system response $h(t)$

Deconvolution

$$X(j\omega) = \frac{Y(j\omega) + noise}{H(j\omega)}$$

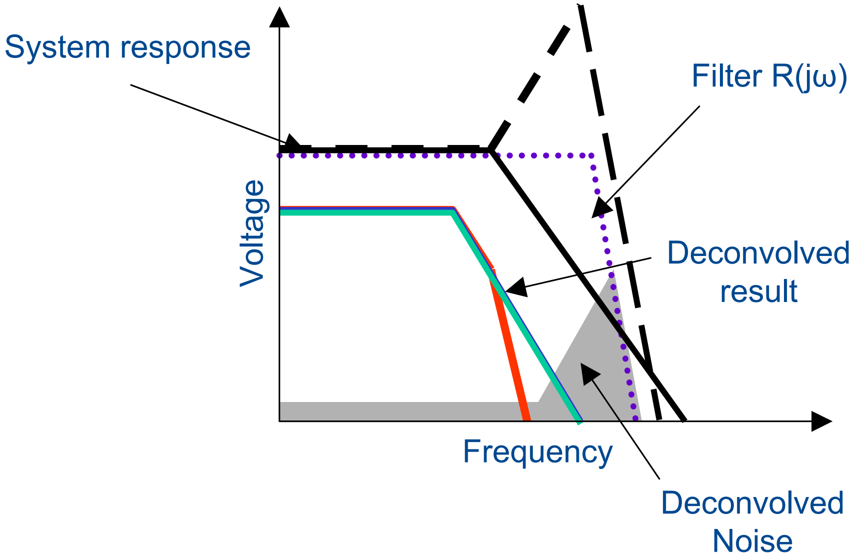
- Inverse problem
- Ill-posed
- Noise
- System response errors



Deconvolution with filter

$$X(j\omega) = \frac{Y(j\omega) + noise}{H(j\omega)} R(j\omega)$$

- Inverse problem
- Ill-posed
- Noise
- System response errors
- Filter added to limit noise/errors



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Deconvolution with filter

$$X(j\omega) = \frac{Y(j\omega) + noise}{H(j\omega)} R(j\omega)$$

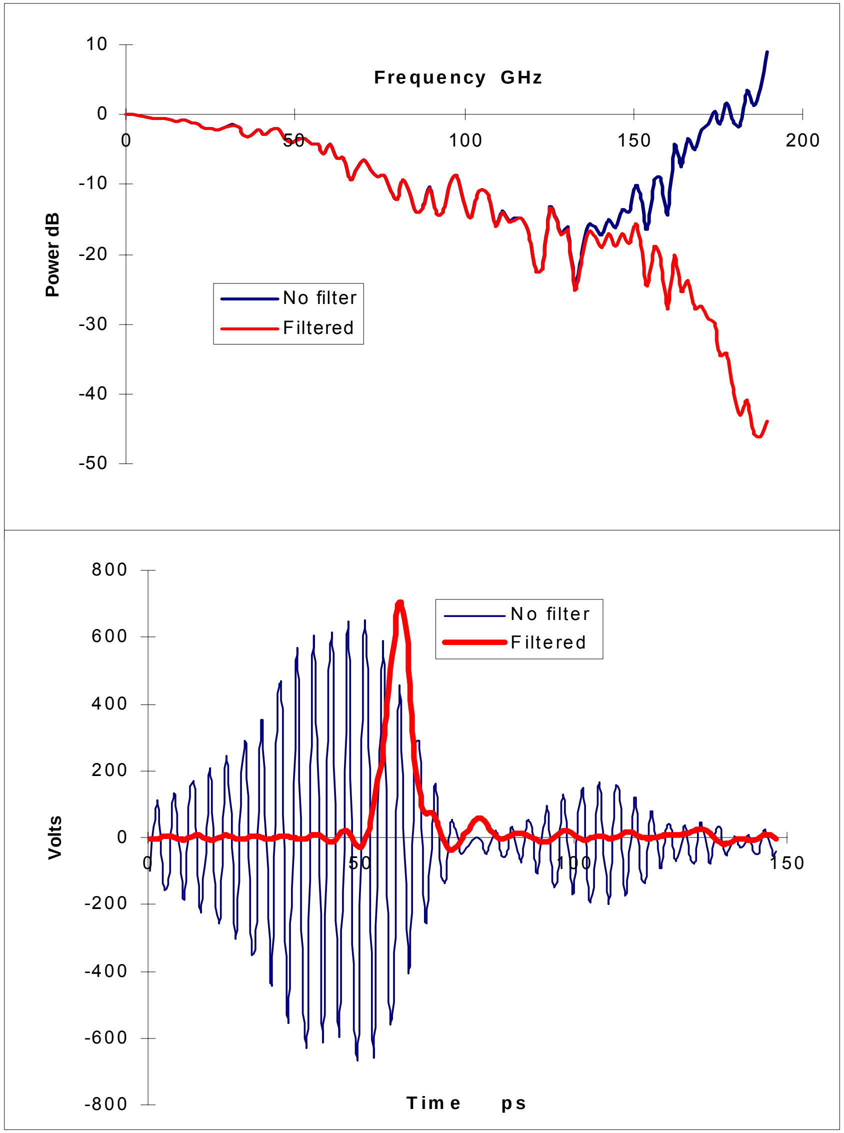
- Inverse problem
- Ill-posed
- Noise
- System response errors
- Filter added to limit noise/errors

Deconvolution of a 10.2 ps pulse with a Gaussian filter of 7.5 ps using:

a) No filter (blue)

b) A filter of effective width 4 ps (red). Resultant width is 6.2 ps

c) cf quadrature (rds) 6.9 ps.



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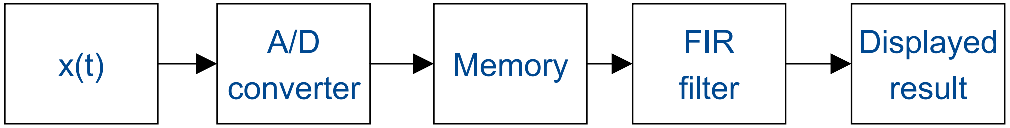
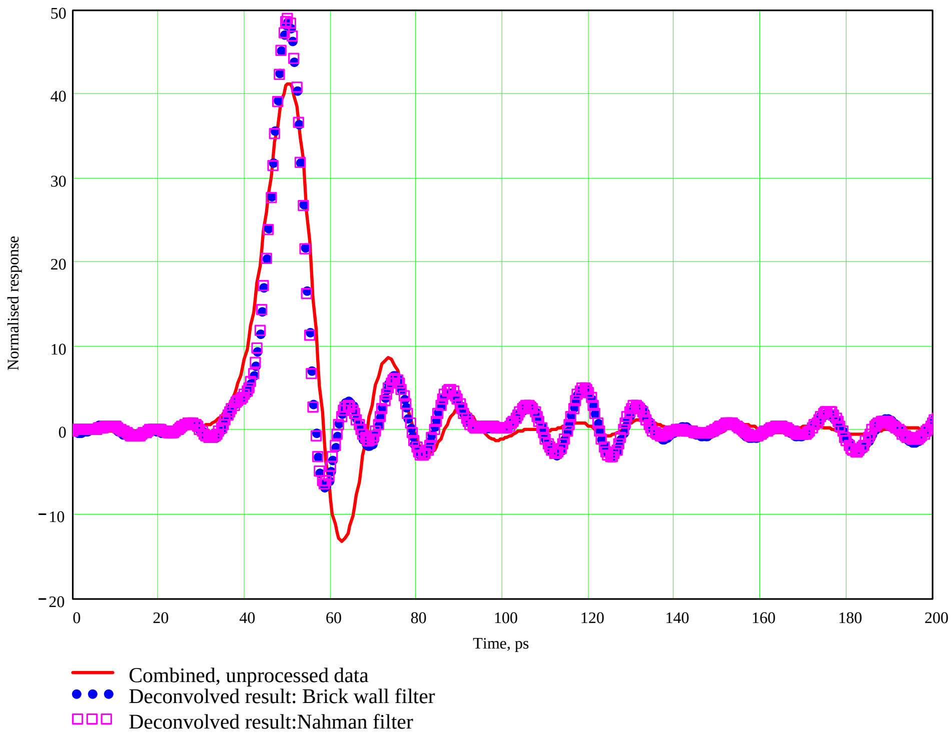
Realisation of Deconvolution process



- System impulse response
- Direct time-domain convolution (Digital filtering - FIR)
- Transform approach (e.g. Fourier transform)

$$R(j\omega) = \frac{|H(j\omega)|^2}{|H(j\omega)|^2 + \alpha |C|^2}$$

1. α is a user controlled parameter
2. C may be constant or frequency dependent e.g. ω^2 maximises the smoothness of the result



Jitter

Analysis and correction of measurement jitter

$$x_m(t) = x(t+\xi) + \varepsilon$$

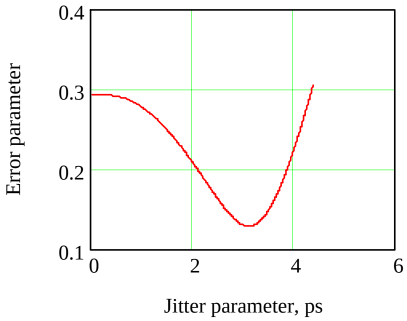
$$\langle x_m(t) \rangle = \int_{-\infty}^{+\infty} x(t-\tau)\phi_{Jitter}(\tau)\, d\tau$$

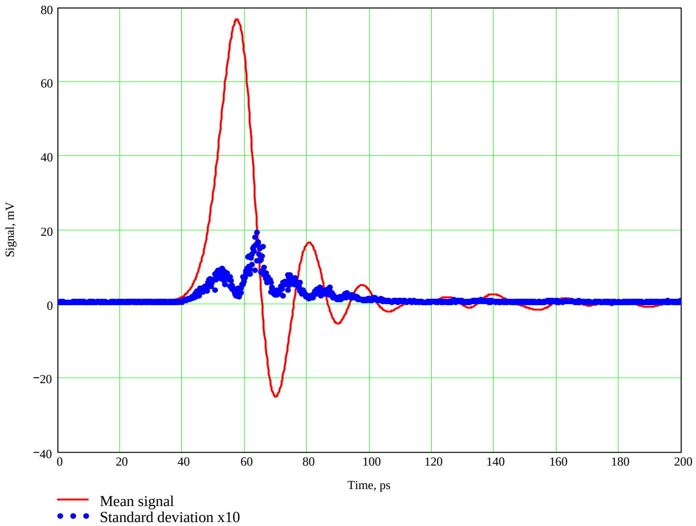
$$x_m(t) = x(t) + \varepsilon + \xi \frac{d\,x(t)}{dt} + \ldots$$

$$\sigma_m^2(t) \approx \sigma_{noise}^2 + \sigma_{Jitter}^2 \left(\frac{d\,x(t)}{dt} \right)^2$$

$$\langle x_m(t) \rangle \approx x(t) + \sigma_{Jitter}^2 \frac{d^2 x(t)}{dt^2}$$

- A measured signal will contain both jitter and noise
- Jitter and noise can be analysed as a Taylor expansion.
- The variance of the signal will be a function of time
- If the jitter distribution is assumed then the underlying signal can be estimated by deconvolution





See M G Cox, P M Harris and D A Humphreys, 'An Algorithm for the removal of noise and jitter in signals and its application to picosecond electrical measurement', Numerical Algorithms, Vol. 5, May 1993, pp. 491-508

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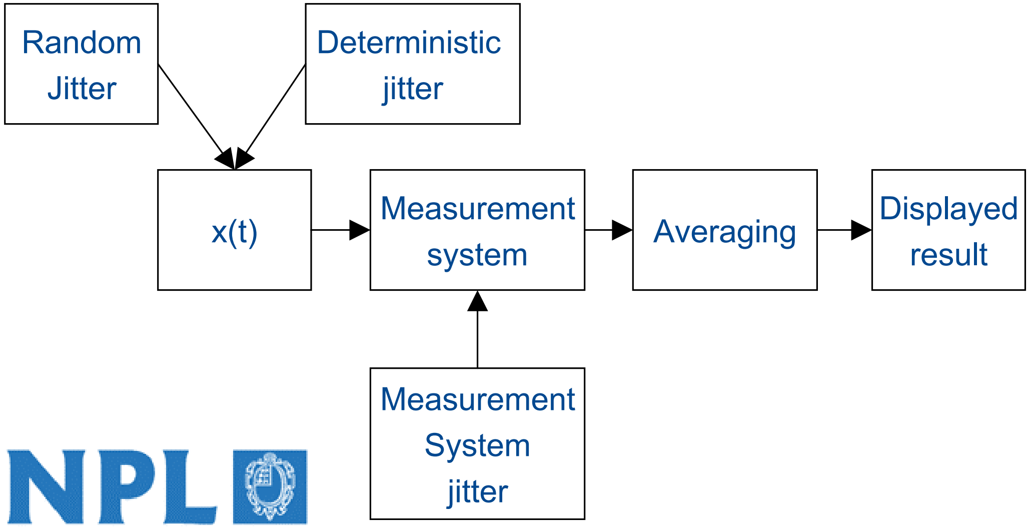
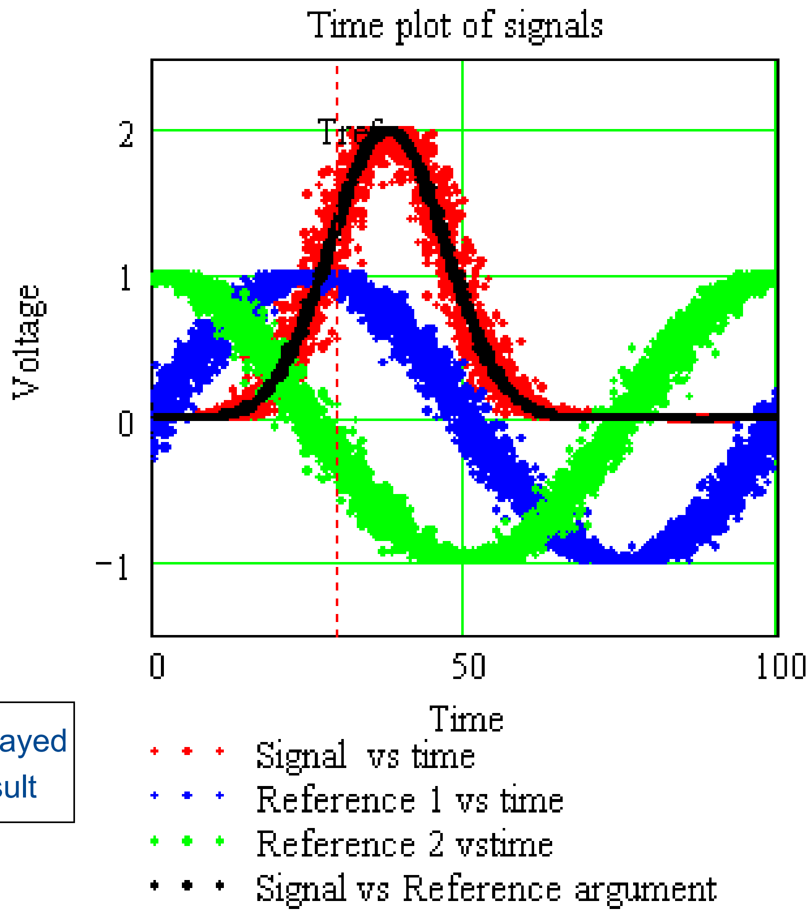
Removal of measurement jitter using time-correlation between sampling gates

- If two sinusoidal signals in quadrature and with the same amplitude are measured using the same trigger event then the sample time can be determined.
- This information can be used to determine the timing of a waveform measured in another channel.





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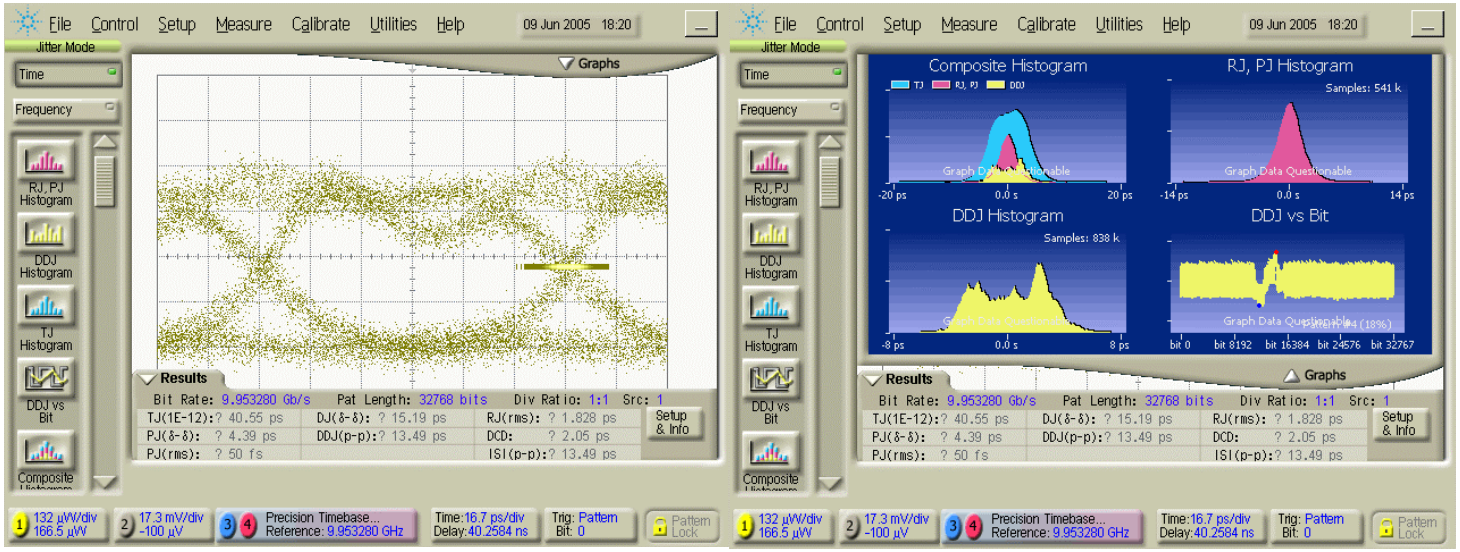
Jitter in datacomms

- Measurement jitter: uncertainty in time between the trigger and measurement events on sampling or real-time digital oscilloscope.
- In Datacomm application the total measured jitter is the combination of data-dependent-jitter DDJ and random-jitter (RJ) in addition to any contribution added by the measurement system.
- As DDJ is to be accurately quantified to qualify components, it is important to minimise the measurement jitter.



See 'Jitter analysis: The dual-Dirac model, RJ/DJ, and Q-scale', White Paper, Agilent Technologies, Inc., February 9, 2005.

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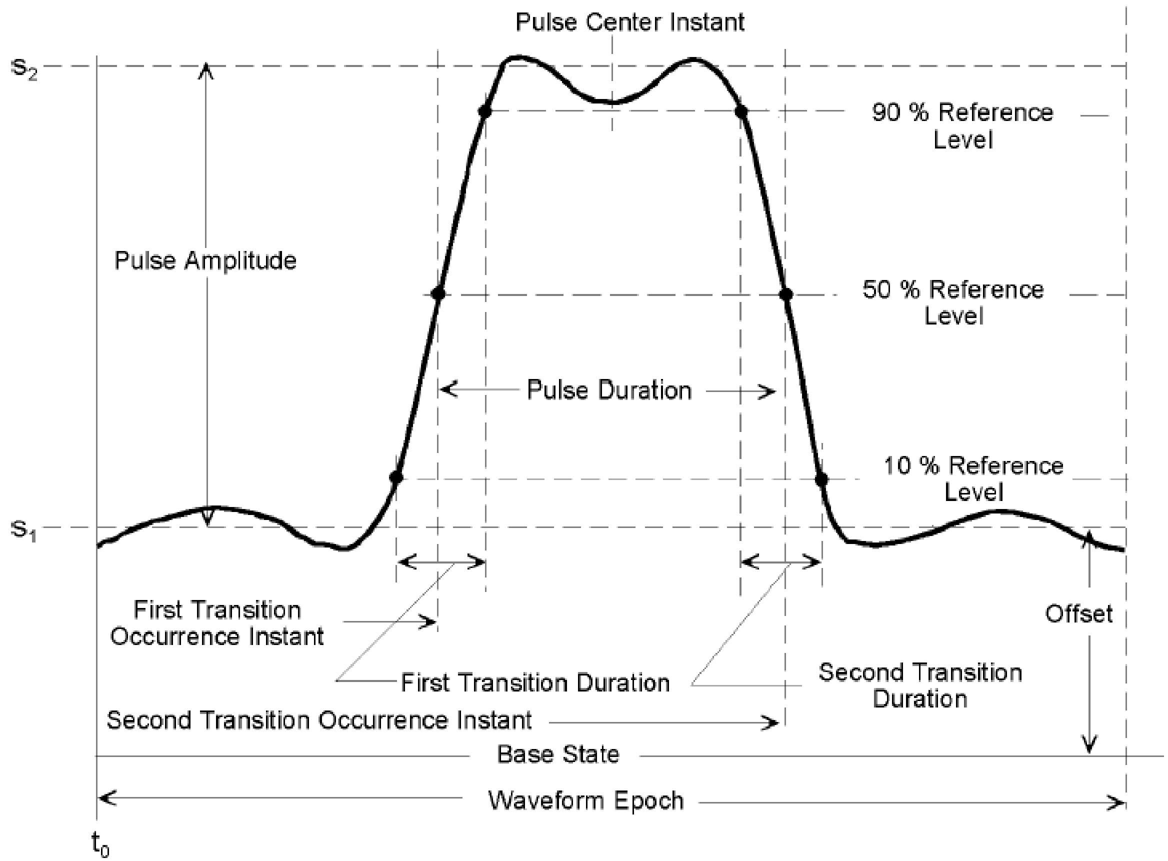
Jitter

- Jitter affects the measured signal by broadening it
- Measure the jitter using oscilloscope software (histogram method)
- Ideally we need to know the jitter distribution
- Usually assumed to be a Normal distribution
- Averaging over too long a period should be avoided since in addition to high frequency jitter, low frequency drift might also occur which produces non-Gaussian shaped jitter
- Removal of jitter - philosophical should it be removed?
- The problem is to identify which jitter is associated with the calibration and which is associated with the measurement

Waveforms and parameters

Parameters for a pulse waveform



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IEEE Standard on Transitions, Pulses, and Related Waveforms, IEEE Std 181, 2003

- Definition of terms
- Definitions for calculation of levels (typically 0% and 100%)
  - Histogram methods and how to apply them (Main technique)
  - Peak magnitude
  - Initial (final) instant
- Definitions for a single transition (positive and negative)
- Definitions for a pulse waveforms
- Definitions for compound waveforms containing several transitions
- Classification of aberrations such as overshoot and undershoot before/after the transition

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Definition of levels

Care must be taken in defining the baseline and topline of the pulse and measuring the risetime, as has been described elsewhere.

waveforms can be measured in two ways:

- **built in acquisition and processing algorithms of the oscilloscope**
- **transferring the waveforms to a computer and processing them with proprietary software.**

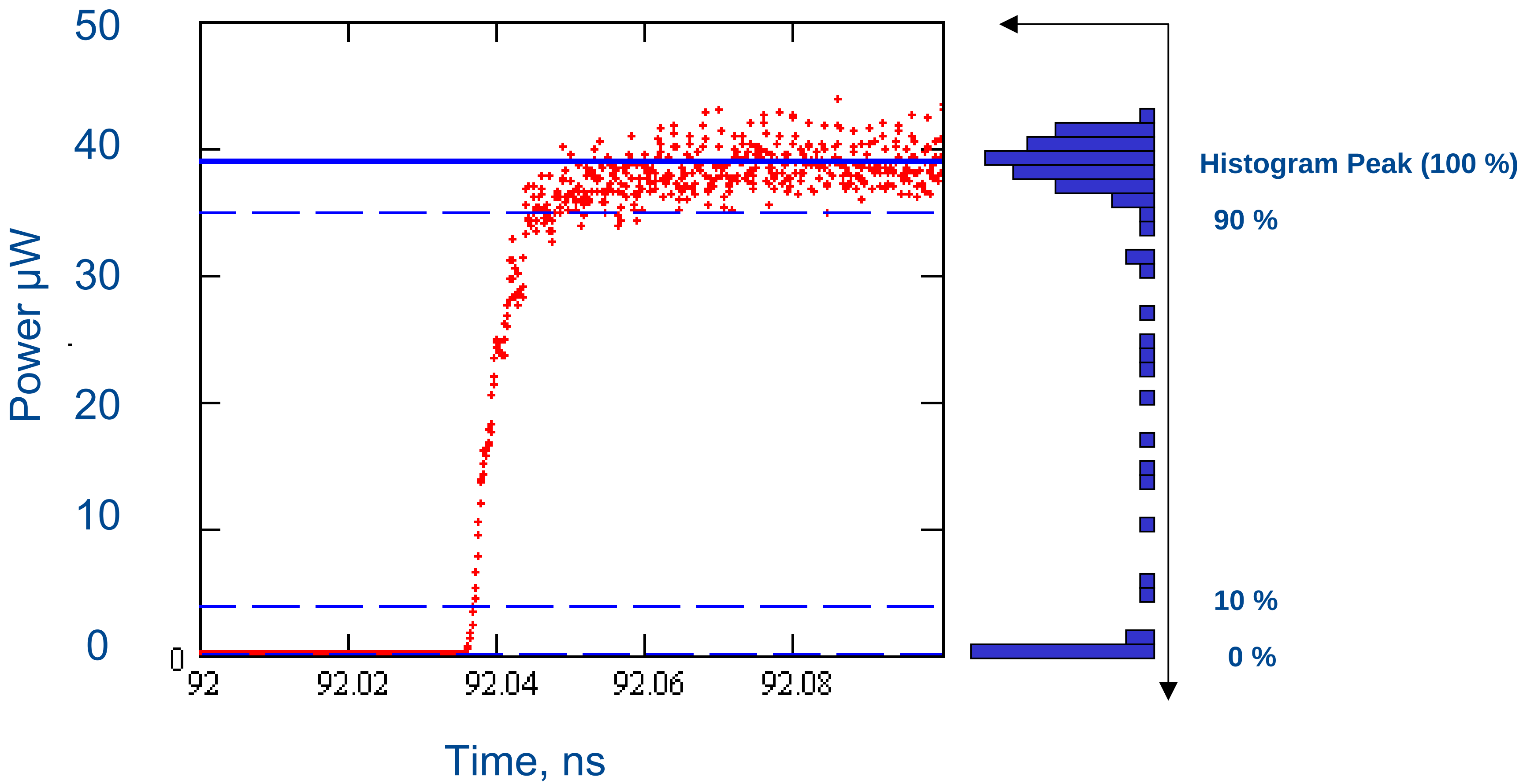
Whichever method is used care must be taken to ensure that the processing method is understood and that it gives the "correct" results, in other words the correct operation can be verified.

Levels must be defined for the specified region of interest.

Record the waveform on the longer epoch and find the levels.Switch off the tracking on the oscilloscope to keep the levels fixed and change the timebase to the faster setting. Record the risetime.

For processing the data by computer use an analogous process

Example of RF transition duration pulse parameters



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N.B. histogram is for example only

Bear traps

- Common Units Power or voltage envelope
- Do the important features occur within the specified ranges?

Parameters defined as |Voltage|

Voltage	Power
100%	100%
90%	81%
50%	25%
10%	1%
0%	0%

Parameters defined as Power

Power	Voltage
100%	100%
90%	94.9%
50%	70.7%
10%	31.6%
0%	0%

David A Humphreys, James Miall, 'Towards The Definition of RF-Pulse Power-Envelope Transition-Duration,' BEMC 2005, Teddington, UK, 14-17 November 2005., ISBN 0 946754 45 4, pp. 50-51.

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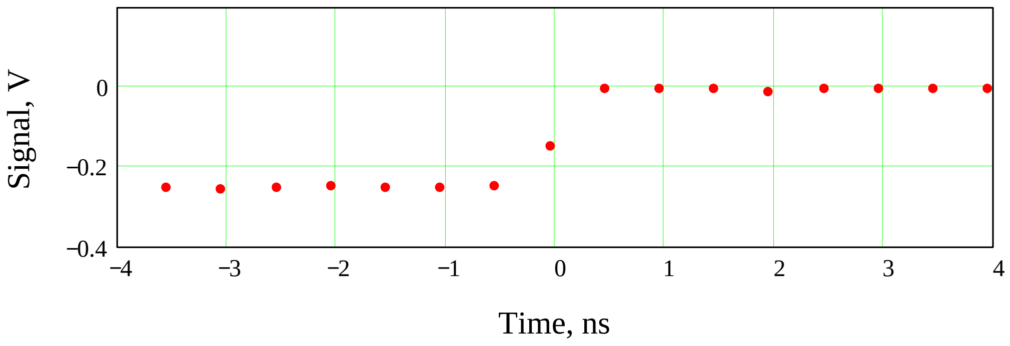
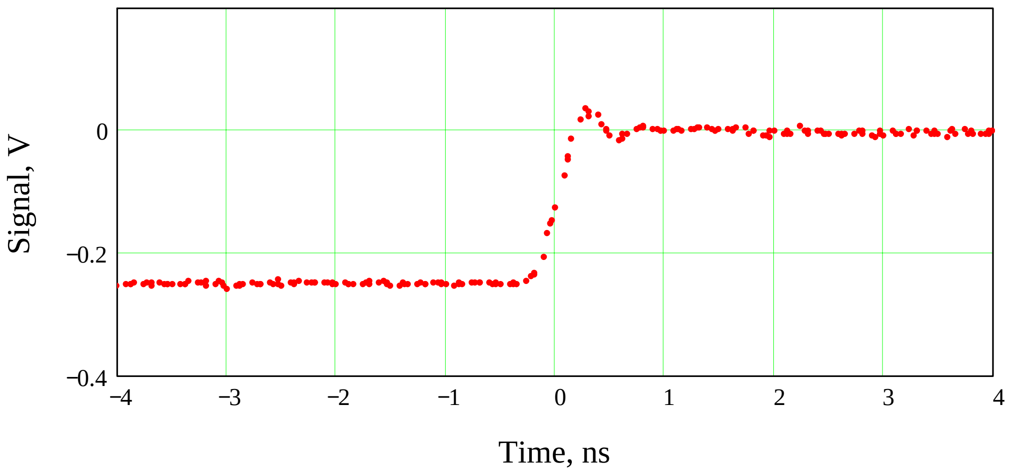
Numerical issues

- Number of points defining the parameter
- Interpolation
- Noise
- Jitter



- 15 Measurements of the response
- Transition duration 316 ps
- 1σ uncertainty due to measurement variations 4.8 ps



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Time and frequency

	Time domain	Frequency domain
Number of points	Np	$Nf = Np/2$
Increment	δt	$\delta f = 1/\Delta t$
Window or epoch	$\Delta t = Np.\ \delta t$	$\Delta f = 1/(2\delta t)$ $= Nf\ .\delta f$

Pulsewidth FWHM 15 ps Bandwidth f_{3dB} 25 GHz							
Time domain				**Frequency domain**		No of points in pulse	No of points in spectrum
Time/div ps	Window ps	No points	δt ps	Max GHz	δf GHz		
20	204.8	512	0.4	1250	5	38	5
50	512		1	500	2	15	13
100	1024		2	250	1.0	8	26
50	512		.25	2000	2	60	13
100	1024		.5	1000	1	30	26
200	2048	2048	1	500	.5	15	51
500	5120		2.5	200	.2	6	128
1000	10240		5	100	.1	3	256

The maximum sampling frequency must be higher than the oscilloscope or source bandwidth otherwise aliasing will occur

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Summary

- Why use parameters?
- Instruments
- Waveform metrology and correction
- Deconvolution
- Jitter
- Parameters

Thank you for your attention

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